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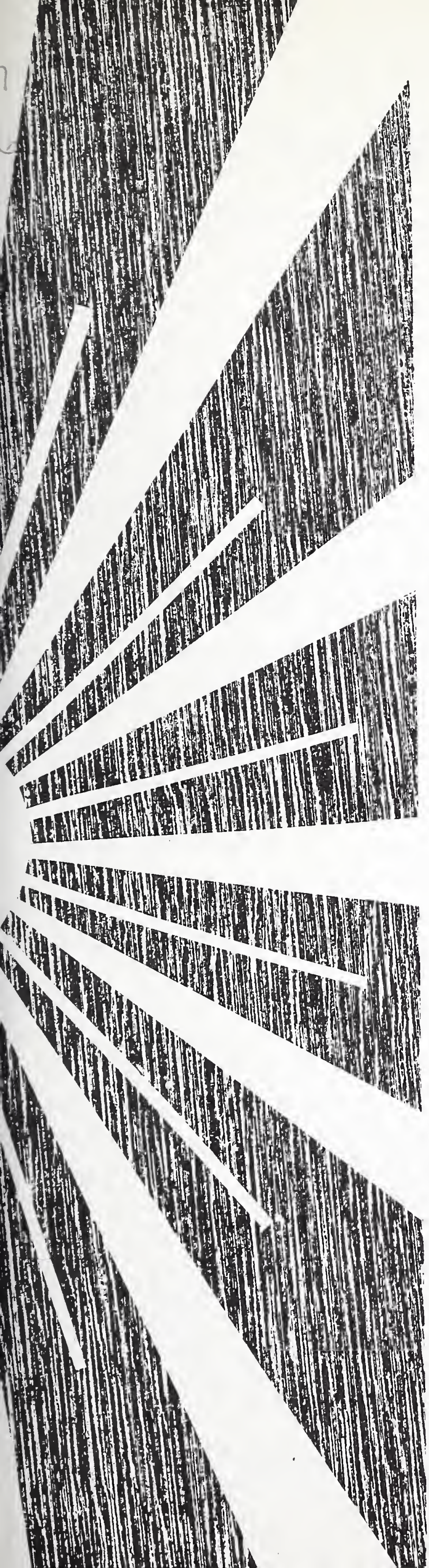

SOLAR DRYING OF WOOD IN LOUISIANA

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Solar Drying of Wood in Louisiana

TIMOTHY G. LUMLEY AND ELVIN T. CHOONG[1]

Introduction

The energy crisis of the 1970's has stimulated research and development of several energy forms. One possible source of clean, inexhaustible energy is the sun.

There are two serious limitations to the effective use of solar energy. Most apparent is the intermittent availability of the energy. A process that requires a constant heat source would necessitate development of some form of energy storage for use at night and on cloudy days. The second major limitation is that solar energy is in a nonconcentrated form. To obtain large quantities of energy, the radiant energy from the sun, called the insolation, over a large surface area must be captured.

When these two limitations are overcome, our most abundant energy source can be harnessed. The sun's unlimited energy supply need not be conserved. Each day's solar energy is free and any not used will be re-radiated back into space. Solar energy produces no toxic waste or pollutants. Because the energy can be captured near its point of use, transportation and distribution costs could be low or nonexistant. Solar energy is a safe energy source, and reliance on it would provide an equitable means to allocate energy resources among generations.

If solar energy could be effectively used to dry lumber, a clean, inexpensive energy source would be available to lumbermen, and part of the nation's energy resources could be conserved. Although most hardwoods are dried at temperatures easily obtained by flat-plate collectors, a large lumber kiln requires much energy to dry green lumber. A large solar collector, with a consequently large capital investment, is therefore necessary to fully utilize solar heat for lumber drying.

Analysis by Lumley and Choong (1979) showed that use of commercial solar collectors at installed prices of $20 per square foot or more was not economically justified in Louisiana at that time. Areas with more usable solar radiation or higher fuel prices might be able to justify somewhat higher collector prices, but even with recent fuel price increases it is doubtful that expensive commercial solar collectors are economically competitive for lumber seasoning as yet.

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For a solar kiln to be commercially feasible, the collector's cost must be reduced. Integrating the collectors into a kiln structure may help by reducing total construction cost. However, a computerized modification of a heat consumption model (Shottafer and Shuler, 1974) that considered diurnal temperature fluctuations of a solar kiln showed that sufficient solar collector area cannot be incorporated into a kiln's structure without some modifications in drying methodology or traditional kiln design. Furthermore, conventional kiln structures are not geometrically optimal for solar collector orientation. If solar collectors could be used to form the exterior surface of the kiln structure, provisions should be made to thermally isolate them from the kiln's interior to prevent nightly heat losses.

Compounding the problem of sufficient heat collection is moisture removal. Wood with a specific gravity of .56 will lose 39.2 pounds of water per cubic foot when dried from a moisture content 120 percent to 8 percent. A 50,000 bd-ft kiln would therefore have to remove 163,333 pounds (19,560 gal) of water. Traditionallty, moisture is removed by venting the moisture-laden air to the outside of the kiln, replacing it with freshly heated air. A venting function in a solar kiln would seem to necessitate some form of heat storage to heat replacement air at night or on cloudy days.

The main purposes of this study were (1) to design, construct, and evaluate a small forced air solar lumber kiln, and (2) to establish the relationship of Louisiana climatic and solar insolation data to solar drying of different wood species. The results of this study provide basic information about the state-of-the-art of solar energy for application in wood processing.

Literature Review

Research during the past 20 years has led to the development of two major solar kiln types, the most common being the so-called "greenhouse" type. These kilns were typically wood frame structures covered on the roof and three walls by translucent glazing materials. Blackened aluminum plates on the interior serve as heat collecting (blackbody) surfaces. Such kilns are inexpensive, easy to design and build, and simple to operate, but tend to have radical diurnal temperature fluctuations due to substantial nightly heat losses. These kilns have been successfully demonstrated on a small scale in the United States (Peck, 1962; Maldonado and Peck, 1962; Chudnoff et al. 1966; Troxell and Mueller, 1968) and in several developing countries (Plumptre, 1967; 1973; Casin et al. 1969) but seem to have practical size limitations because the volume (capacity) of such structures increases faster than the surface area needed to collect solar energy.

A second type of solar kiln consists of an enclosed drying chamber and some form of external (to the chamber) collector. The drying chamber can be insulated to reduce diurnal temperature fluctuations and thus give more control over drying conditions, but these kilns are more complicated and expensive.

Read et al. (1974) built a solar kiln at Griffith, Australia. The kiln has approximately 600 ft^2 of solar collector inclined 38° to the horizontal. The collectors had a single glass glazing, and chemically applied, spectrally selected blackbody coating. Kiln capacity was 1,200 bd-ft and the S/L[2] ratio was 0.50ft^2/bd-ft. Air was circulated in the kiln by two 30-inch fans and through the solar collector by a small centrifugal fan. A rock pile thermal storage bed that provided about 16 hours of heat recovery per day was located under the kiln. Alpine ash lumber dried to 16 percent MC[3] in 20 days while a matched pile air-dried to only 42 percent MC in the same period.

Tschernitz and Simpson (1977) of the U.S. Forest Products Laboratory conducted a study to determine the feasibility of utilizing solar energy for lumber drying in developing countries. They indicated that the greenhouse-type kiln would not have the drying capacity to meet the necessary production rates when drying green lumber. They built a kiln which utilized an external collector horizontally oriented in which air was circulated. The absorbing surface was charcoal-covered soil, which provided some heat storage capacity. This kiln has about 4,000 bd-ft capacity and the S/L ratio was 0.24 ft^2/bd-ft. Initial run indicated that red oak could be dried in Madison, Wisconsin from 60 percent to 10 percent MC in 28 days during the summer.

The solar kiln at Virginia Polytechnic Institute (Oliveira, 1979) is actually a semi-greenhouse type, having a capacity of 150 bd-ft and provided with a 20-inch circulating fan. The kiln has the advantage of being insulated in all walls except the south wall, in order to minimize heat loss. Both the south-facing vertical wall and the south-facing sloping roof (45°) were double glazed with transparent polyester film. All other walls and the floors were insulated frame construction. Solar drying of oak from about 80 percent to 30 percent MC took 9 weeks in the spring, which was three-fourths as much time as air drying. Both the rates of drying and the final quality of the solar-dried lumber were superior to those of the air-dried lumber.

A solar kiln built by the U.S. Forest Service in Carbondale, Illinois (Chen and Rosen, 1979) used recycled aluminum beverage cans for the collector plate and a double-paned Fiberglas cover. The drying chamber was insulated. Air was circulated with a reversible and variable-speed fan.

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[2]S/L ratio refers to ratio of solar collector glazing area to lumber capacity.

[3]MC refers to moisture content of wood based on oven-dry conditions.

The relative humidity inside the kiln was controlled so that any excess moisture could be vented out. Yellow poplar was reported to be effectively dried in all seasons of the year 2 to 3.5 times faster by solar kiln drying than by air drying, but the drying rate in the kiln was initially slower. This kiln was later modified to include a dehumidifying system (Chen et al., 1980), and preliminary results indicate that yellow poplar could be dried faster and to a lower moisture content than by either solar or dehumidification drying alone.

Climate of Louisiana

Any study into utilization of solar energy requires appropriate climatic data for accurate engineering design specifications. For solar drying, the appropriate parameters are temperature, relative humidity, and insolation. Rainfall is indirectly important because of its effect on the other three. Unfortunately, obtaining specific design values for these variables is difficult because of considerable diurnal, seasonal, and geographic fluctuations.

A subtropical latitude and abundance of water bodies are the major determining factors of Louisiana's climate. Prevailing winds are southerly during the summer providing warm, moist air and frequent afternoon thunderstorms. During the winter, warm southerly winds alternate with cold continental air masses to produce varying length cycles which typically contain a period of rain with dropping temperatures, a period of cold, crisp days, and then a slow warming trend until the cycle is repeated.

Temperature

According to the National Oceanic and Atmospheric Administration (NOAA, 1976), the average annual temperature ranges from 66°F to 69°F in Louisiana. Average January and July temperatures are 49°F and 83°F in the northwest and 57°F and 81°F in the southeast, respectively. The cooler summer temperatures in the southern parts are due to the cooling effect of almost daily showers in the parishes near the Gulf. The number of days with freezing temperatures ranges from 24 at Shreveport to 4 at New Orleans.

Rainfall

Additional NOAA (1978) data indicate mean annual precipitation ranges from 46 inches in Caddo Parish to as much as 66 inches near the Gulf coastal areas. During the summer months, rainfall is highest in the southern portions of the state with almost daily showers in the coastal parishes. During the winter months, the northern parishes receive more rainfall because of cold air masses that stall and produce heavy rainfall where the cold continental air and the warm Gulf air meet. Showers and thunderstorms occur on an average of 50 to 60 days a year in the northwest and north-central areas, 60 to 70 days in central and northeast areas, and 70 to 80 days in south Louisiana. During fall, winter, and early spring, thunderstorms may occur any time of the day, but from late spring through summer most of the thunderstorms take place in the afternoon.

Solar Insolation

Unfortunately, insolation records, the most important data for solar energy research, are lacking. Daily insolation was measured prior to 1957 at the New Orleans weather station for 16 years, at the Lake Charles weather station for 11 years and the Shreveport weather station for 4 years. Monthly summaries are given in Table 1. The data indicate substantial differences among the cities, but there is insufficient data to develop a model to explain the source of this variability. Mean percentage of possible sunshine and mean number of hours of sunshine, two variables that affect solar insolation, are given for New Orleans and Shreveport in Table 2.

Table 1.—Mean daily solar radiation, by month, for three cities in Louisiana

Month	Solar radiation		
	Lake Charles	New Orleans	Shreveport
	....	(Langleys)[1]	....
January	245	214	232
February	306	259	292
March	397	335	384
April	481	412	446
May	555	449	558
June	591	443	557
July	526	417	578
August	511	416	528
September	449	383	414
October	402	357	354
November	300	278	254
December	250	198	205
Average	418	347	400

Source: U.S. Climatic Atlas. U.S. Dept. Commerce (1968).

[1] Langleys (Cal/cm^2) = 3.687 Btu/ft^2

Table 2.—Mean percentage of possible sunshine and mean number of hours of sunshine, by month, for two cities in Louisiana

Month	Sunshine			
	New Orleans		Shreveport	
	(%)	(Hrs)	(%)	(Hrs)
January	49	160	48	151
February	50	158	54	172
March	57	213	58	214
April	63	247	60	240
May	66	292	69	298
June	64	287	78	332
July	58	260	79	339
August	60	269	80	322
September	64	241	79	289
October	70	260	77	273
November	60	200	65	208
December	46	157	60	177
Average	59	228	69	251

Source: U.S. Climatic Atlas. U.S. Dept. Commerce (1968).

Climatic Patterns

Mean monthly climatic parameters at 3-hour intervals for four Louisiana weather stations were obtained (NOAA, 1978) to analyze Louisiana's climatic patterns. The National Weather Service Stations at Baton Rouge, Lake Charles, Shreveport, and New Orleans were chosen to achieve a geographic cross section of the state. Data were collected on five variables from January 1973 to August 1978. The five variables were cloud cover, temperature, wet-bulb temperature, relative humidity, and wind speed. Additionally, equivalent equilibrium moisture content (EMC) of wood was computed from the temperature and relative humidity data for each observation. Observations were at 3-hour intervals.

The statistics from 2,208 observations are given below:

	Mean	Standard deviation	Range
Dry bulb temperature (°F)	66.6	13.1	30.0- 96.0
Wet bulb temperature (°F)	61.4	11.5	29.0- 80.0
Relative humidity (%)	75.3	12.9	41.0-100.0
Equivalent EMC of wood (%)	15.3	4.0	5.4- 28.4
Cloud cover (1/10's)	5.5	1.4	1.0- 9.0
Wind speed (mph)	8.0	2.7	0.4- 16.9

Analysis of variance indicated that city, month, and time of day have highly significant effects on these variables. Figure 1 shows mean monthly temperature, humidity, and EMC for the four cities. The mean monthly climatic parameters at 3-hour intervals are presented in Table 3.

Materials and Methods

Solar Kiln Prototype

Wengert (1971) established the following energy use distribution for a greenhouse kiln at Fort Collins, Colorado:

	%
Conducted through north wall	1.5
Conducted through floor	11.4
Convection, roof and walls	29.1
Storage inside drier	7.4
Solar, outgoing	17.5
Longwave heat	13.2
Ventilation	14.4
Water evaporation (latent heat)	15.4

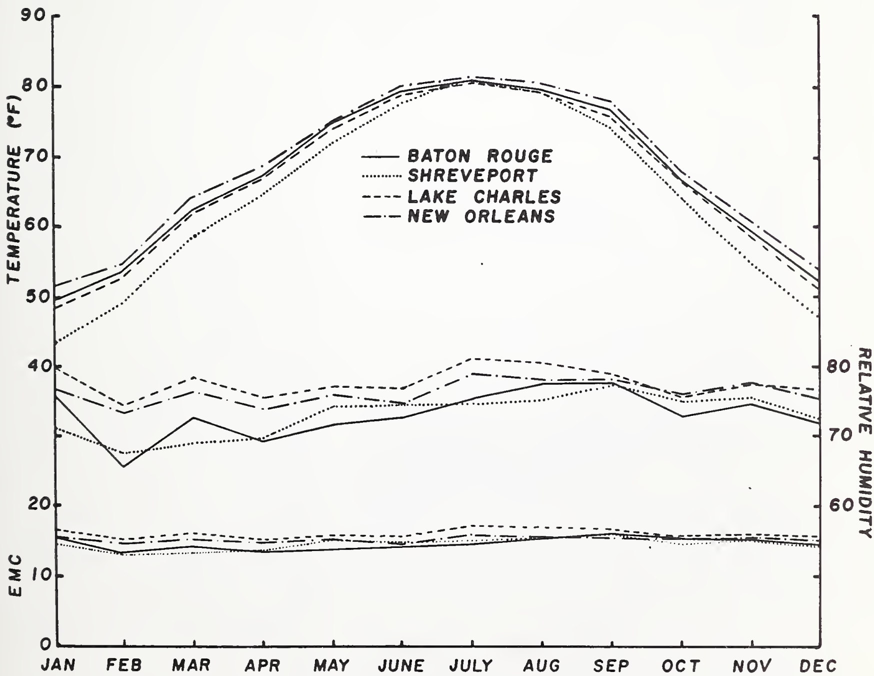

Figure 1.—Mean monthly temperature, relative humidity, and equivalent equilibrium moisture content of wood in four Louisiana cities.

Table 3.—Mean yearly climatic parameters at 3-hour intervals

Time	Temperature	Wet-bulb temperature	Relative humidity	EMC[1]	Cloud cover	Wind speed
	(°F)	(°F)	(%)	(%)	(1/10's)	(mph)
Midnight	62.6	59.8	84.6	18.0	4.6	6.6
3:00 AM	60.8	58.7	87.4	19.4	4.9	6.0
6:00 AM	59.9	58.0	88.3	19.9	5.6	5.9
9:00 AM	67.3	62.1	75.0	14.5	5.8	9.2
Noon	73.2	64.3	61.6	11.2	6.0	10.2
3:00 PM	74.6	64.5	58.2	10.5	6.0	10.5
6:00 PM	69.9	62.9	67.3	12.6	5.6	8.4
9:00 PM	64.7	61.0	80.0	16.2	4.9	6.9

[1]EMC refers to moisture content of wood in equilibrium with atmosphere.

Only 15.4 percent of the incoming energy was used for the intended purpose of drying wood. Conduction and convection accounted for the largest energy losses (42 percent) and were associated with the low thermal insulation characteristics of greenhouse kilns. Radiant losses of 30.7 percent were associated with the transparent walls of the drying chamber. These heavy losses seemed inefficient, so a kiln with external solar collectors was designed.

Drying Chamber

Theoretical Considerations—Use of an external solar collector allows isolation of the drying chamber from convective and radiant heat losses. Of course, the chamber must be well-insulated and opaque. The negative aspects are the additional expense and possibility of heat losses in the ducting system. Using the collectors as structural surfaces (but keeping them thermally isolated from the drying chamber) will tend to lower the heat losses but tend to constrain the size and orientation of the collectors.

Heat losses during venting cause no serious operational problems in a conventional kiln as the incoming air can be easily conditioned to the proper temperature and humidity. Such losses, however, cost money. In a solar kiln these heat losses may create problems as the energy source is limited and reheating incoming air by solar means may be difficult. Computer simulation showed that losses in venting may involve as much as 25 percent of the heat required for a solar kiln, particularly in regions with high humidities or low temperatures. Additionally, venting at night cools down the lumber pile, preventing a buildup of thermal inertia. However, due to diurnal temperature fluctuations of a solar collector, the possibility of water removal by condensation exists. This would eliminate the need for venting, providing the following advantages: (1) heat loss from venting the kiln would be saved, and part of the heat of vaporization might be recovered as moisture condenses; (2) reduction of heat losses at night would allow the kiln to maintain higher average temperatures; (3) as drying progressed and less water was removed from the wood, the relative humidity of the kiln would automatically decrease.

Isolation of the drying chamber leads to an interesting possibility for solar heat storage—the wood pile. The specific heat of dry wood (c_o) is $c_o = 0.25 + 0.0006(t)$, where t is temperature (°F). The specific heat (c) of wet wood is given by

$$c = \frac{m+c_o}{1+m} + A$$

where m is the fractional moisture content of the wood and A is the increases in specific heat due to wood-water bond energy—it ranges from

0.04 at 85°F to 0.09 at 140°F (U.S. Forest Products Lab., 1974). A comparison of heat storage capacity for wood (assuming a specific gravity of 0.56 and wood temperature of 100°F) at several moisture contents with other sensible heat storage media is shown below:

Material	Density (D)	Specific heat (c)	Volume heat capacity (D•c)
	(lbs/ft^3)	(Btu/lb-°F)	(Btu/ft^3-°F)
Water	62.43	1.00	62.43
Iron shot	490.68	0.13	63.79
Rock	156.07	0.20	31.21
Wood (20% MC)	41.90	0.53	22.14
Wood (60% MC)	55.90	0.64	35.71
Wood (120% MC)	76.90	0.89	68.30

Rock is probably the most common heat storage medium for solar air systems because of its relatively high heat storage capacity and low cost. Wood, particularly wet wood, is competitive in heat storage capacity, especially when considering the large wood volume already present in a large lumber kiln. Using the lumber pile as heat storage would eliminate the expense and complication of an external storage system.

Relying on the wood pile for heat storage will, however, result in less stable temperature conditions than could be obtained with an external storage system because the wood can only moderate diurnal temperature fluctuations. An external heat storage system would moderate the diurnal temperature fluctuations outside the kiln thus allowing the drying chamber to maintain average conditions. Maintaining constant wood temperature, however, is not the most important consideration—effectively utilizing the captured heat is. If the drying chamber is thermally isolated at night, the only loss of heat energy from the wood would be due to evaporative cooling. The stored heat would therefore promote drying by increasing evaporation (above fiber saturation point) or accelerating bound water diffusion (below fiber saturation point).

Implementation—The experimental solar kiln built at Louisiana State University was fitted into an existing 8-ft by 8-ft by 12-ft concrete block-house with a poured concrete foundation and prestressed concrete roof. A 6-ft by 6-ft by 4-ft drying chamber was built on the inside of the block-house. The walls, floor, and ceiling of the chamber consisted of 4 inches of (K-13) cellulose fiber insulation, a polyethylene vapor barrier, and 1/3 inch epoxy-coated, tempered hardboard. A 24-inch high-volume axial fan powered by a 1½ horsepower motor provided air circulation through a 34-inch by 34-inch by 6-foot lumber pile (approximately 360 bd-ft 8/4 lumber) using 1-inch stickers. Two 12-inch ducts led to a solar collector mounted on the roof.

Evaporative moisture from wood was used to provide humidification in the system, which is necessary in the initial drying of refractory hardwoods to prevent excessive degrade. Moisture in the kiln was removed as condensate through drain holes on the bottom of the kiln and during periodic moisture content measurements when the kiln door was opened.

Box-Type Solar Collector

Theoretical Considerations—Standard flat-plate collectors seem to have three limitations in solar kiln design.[4] One is that optimum collector orientation does not coincide with traditional geometrical configurations of dry kilns. Secondly, a flat-plate collector with the same surface area as a conventional kiln could not possibly supply the necessary heat. Finally, seasonal variations in the sun's altitude cause under-utilization of a fixed-position flat-plate collector at certain times of the year.

To overcome these difficulties, a "box-type" solar collector was envisioned. This collector resembles a large box cut diagonally through opposite corners (Figure 2). The three walls and floor of the box serve as heat collecting surface, and the diagonal plane is the solar glazing. Although no mention of this configuration was found in the literature, it seems to have some conceptual advantages over a flat-plate collector. First, the solar absorption area is increased more than 100 percent over that of a standard flat-plate collector with the same amount of glazing.[5] This results in more heat transfer surface and more potential for collection of diffuse solar radiation. Second, radiation from varying angles during different seasons or times of the day will be more nearly perpendicular to one of the four absorbing surfaces in a box collector than it could be to a stationary flat plate. As shown in Figure 3a, winter sun rays are nearly perpendicular to the vertical surface while summer rays are perpendicular, or normal, to the horizontal surface. Likewise, early morning or late afternoon sunshine will be nearly perpendicular to the east- or west-facing plane. Normality of radiation to collecting surface results in higher absorbance. Part of the energy striking a flat-plate collector is reflected back to the atmosphere. The box collector's geometry, as shown in Figure 3b, will usually allow

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[4]A preliminary study of solar drying was made using a flat-plate solar collector as the heat source. The results from drying elm, hackberry, sweetgum, and sycamore have been published by Lumley and Choong (1979).

[5]It is recognized that the amount of solar energy that strikes the collector glazing area determines the gross energy input into the collector system. The glazing area becomes a critical factor in a flat-plate collector if the absorbance is better than 90 percent efficiency. However, when collector efficiency is less, as is the case with a low-cost system, reflectance off the absorber panel becomes important.

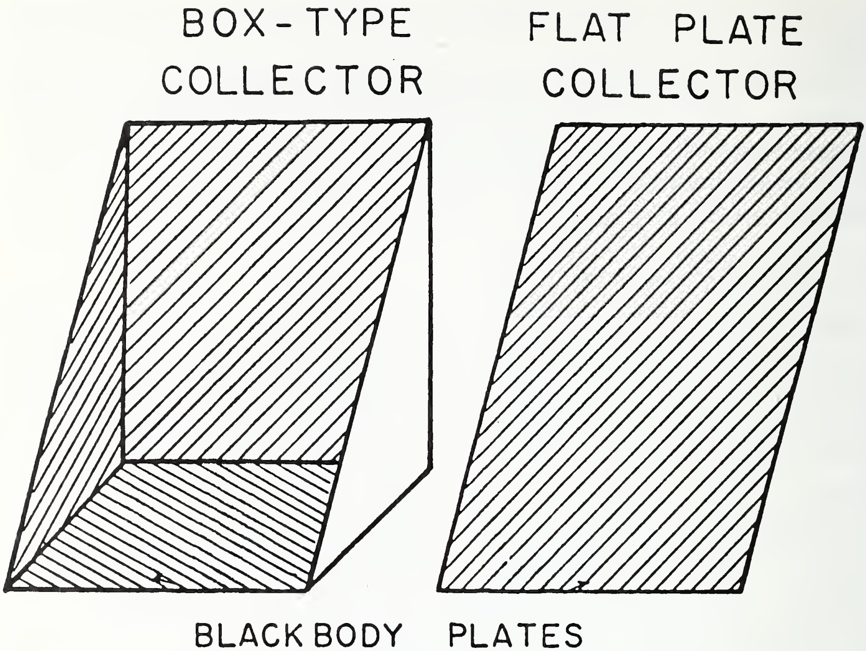

Figure 2.—Comparison of box-type solar collector with a standard flat-plate collector.

reflected radiation to strike another absorbing surface before being reflected back toward space. Finally as shown by Lumley and Choong (1979) the box-type collector can be integrated into a solar kiln structure.

An interesting aspect of the box collector is that manipulation of the dimensions of the glazing[6] or angle at which the glazing is inclined significantly affect the size and orientation of the blackbody. Small glazing angles tend to have large horizontal but small vertical collection surfaces, whereas large glazing angles tend toward large vertical areas with small horizontal ones. Manipulation of the glazing angle will therefore allow flexibility for establishing seasonal collection priorities. For instance, to increase winter heat collection, the glazing angle is increased, enlarging the area of vertical blackbody which is more normal to winter insolation.

Altering the length (inclined edge of glazing) and width (horizontal edge of glazing) of the solar glazing affects width and the blackbody area. The area of horizontal and vertical blackbody can be shown mathematically to be equal for the two orientations, but the amount of east- and west-facing

[6]Glazing is a thin layer of material (e.g. glass, plastic, etc.) that allows passage of short wave radiation from the sun.

collector area increases as width is decreased and length of the glazing is increased. Shadows, of course, play an important part in this collector's performance. A point will be reached where the increase in surface area is offset by losses due to shading.

Implementation—The box collector used on the experimental solar kiln

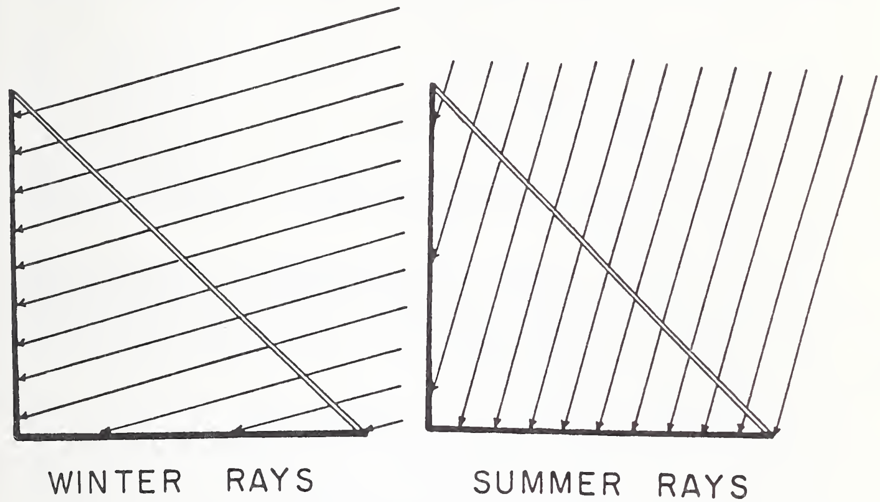

Figure 3a.—Incident angle of solar radiation during two seasons. The perpendicular collecting surfaces allow constant interception of solar radiation in all seasons.

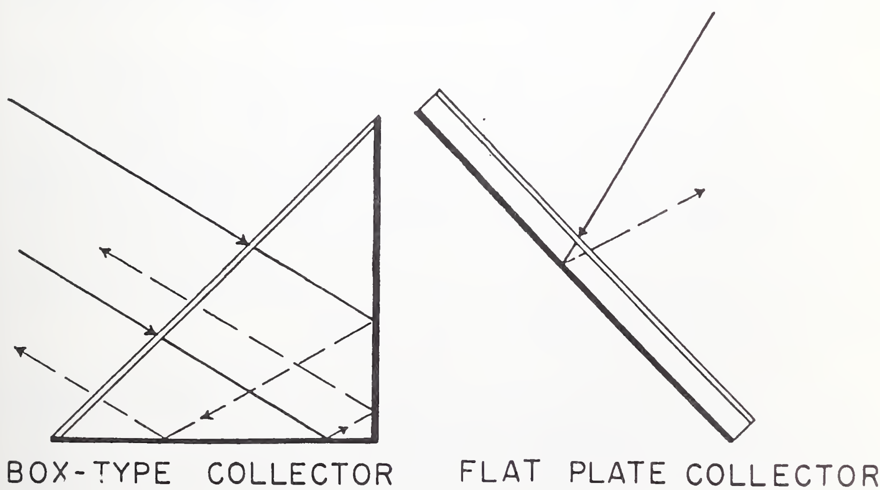

Figure 3b.—Comparison of reflected radiant losses for two collector configurations. The box-type collector allows reflected radiation a second chance to be absorbed by another collector surface.

has a 3.5-ft wide by 7.5-ft long (26.25 ft^2) sheet of (Kalwall Sun-Lite Premium II) fiberglass reinforced polyester glazing inclined at a 49° glazing angle. The ratio of solar glazing area to lumber volume is approximately 0.073 ft^2/bd-ft.

To arrive at the optimal glazing angle, a computer model was developed. While holding the size of the collector glazing constant, the area of horizontal, vertical, east-, and west-facing collector surfaces were computed for hypothetical boxes varying by one degree in glazing angle. After correcting for the effect of internal shadows, Kusuda and Ishii's (1977) tabulation of solar radiation data for various surfaces was used to integrate hourly heat collection over a 1-year period for the various collector configurations. The simulation showed that maximum year-round heat would be provided by the 49° pitch.

A cross-sectional view of the solar kiln (Figure 4) shows the solar collector is connected to the drying chamber by two vents running through the roof. At night the vents to the solar collector are closed, and air circulates within the drying chamber.

Several controlling and recording instruments were used in the solar drying project to provide automatic control of kiln operation and continuous monitoring of drying conditions. The dampers on vents leading to the solar collector are actuated by two (Honeywell Modutrol) electric damper motors. The damper motors are activated by a (Hawthorn) differential thermostat that compares solar collector temperature to drying chamber temperature and opens the vents when the positive temperature differential exceeds approximately 20°F.

A mist humidifier was installed in the kiln to provide control over humidity conditions. The humidifier could be manually operated, or controlled by a (Hygrodynamics) humidity controller at any set RH condition. The humidification system was never used, however, as the kiln's relative humidity remained at appropriately high levels from the moisture content in the wood during the initial stages of drying. Kiln humidity was monitored by a (Honeywell) electronic wet-bulb/dry-bulb circular chart (12 inch) recorder. The psychrometer assembly was placed on the outgoing-air side of the lumber pile.

A (Honeywell) thermocouple temperature recorder measured temperature at various points inside the kiln and solar collector. External ambient temperature was also measured. Type K thermocouples (iron/constantan) were used with the recorder which was calibrated for a temperature range of 0°F to 500°F. The instrument was sensitive to ±1°F. Outside relative humidity was monitored by a (Honeywell) mechanical circular (8 inch) chart recorder. A (Li-Cor LI-550) printing solar insolation integrator measured daily solar radiation.

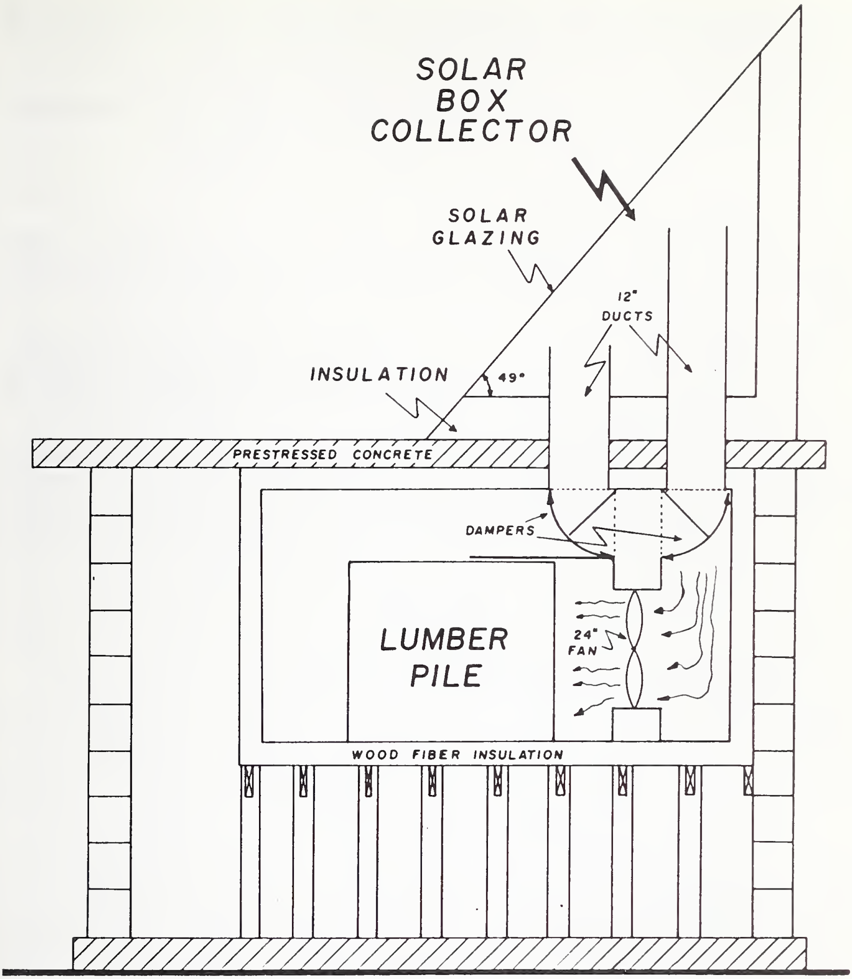

Figure 4.—Cross-sectional view of experimental solar lumber kiln.

Experimental Design

Sampling Design

Six loads of lumber were dried in the experimental solar-heated kiln. They were, in chronological order, 8/4 ash, 8/4 hackberry, 6/4 red oak, 4/4 ash, 4/4 cypress, and 6/4 red oak. Each load consisted of at least 44 6-ft boards, mostly 8 inches wide. Loads of 1-inch lumber had more samples to fill the kiln's capacity. Lumber was obtained green from a local sawmill in 12-ft lengths, cut in half to 6 ft, and end-coated with a commercial sealer.

Four or five 6-ft sections (depending on width) were cut into 2-ft sections to provide kiln samples and matched air drying samples as shown in Figure 5. These samples were also end-coated. A moisture content section was cut from between the air and kiln samples to estimate initial moisture content. The lumber was undressed No. 2 or No. 3 common grade.

Data Collection and Analysis

Data collected for the drying experiments can be grouped into four categories: (1) drying conditions, (2) drying rate, (3) drying charge, and (4) climatic conditions.

Drying Conditions—Kiln drying conditions are determined by temperature, relative humidity, and air velocity. Air velocity was held constant at approximately 400-500 fpm and therefore was not a variable factor. Dry-bulb and wet-bulb temperatures were recorded at 1-hour intervals and transferred to computer cards. Blackbody temperature, ambient temperature, and ambient relative humidity were also coded on the cards at 1-hour intervals. Relative humidity and equilibrium moisture content are normally determined with use of tables or psychromatic charts. This method is quite adequate with the steady-state drying conditions found in most dry kilns, but it is too cumbersome for the constantly fluctuating conditions of a solar kiln. A computerized computational method was therefore designed.

Drying Rate—Four or five matched air and solar kiln samples were weighed on a (Pennsylvania Scale Co.) weighing balance (accurate to 0.01 lb) each morning, except on weekends and holidays, to determine drying rates. After drying was complete, these samples were ovendried so that the exact moisture contents could be calculated and a drying curve determined.

Drying Charge—Each of the 6-ft boards was weighed before and after drying. A (Delmhorst) resistance moisture meter was used to estimate the final moisture content by averaging observations from several measurements on each board. Moisture meter prongs were driven approximately

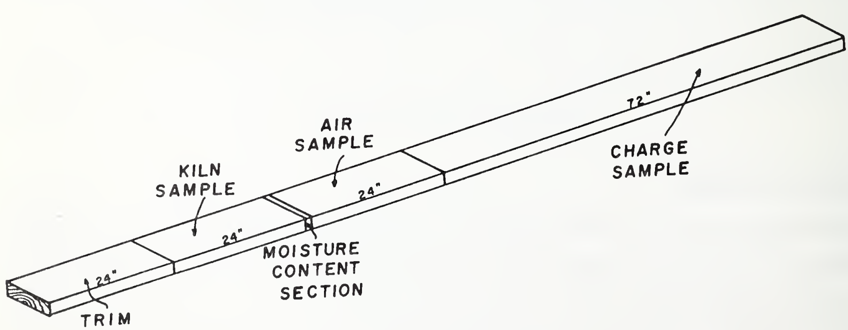

Figure 5.—Sample preparation for kiln, air, and charge samples.

halfway into the boards. After drying, each board was also evaluated for drying defects. Warp was determined by measuring maximum bow, crook, twist, and cup to the nearest 1/32 inch. Bow and crook were measured by placing each end against an 8-ft steel straightedge and determining the maximum distance from the straight edge to the wood surface. Twist was determined by holding three corners against a plane surface and measuring the elevation of the fourth corner. Cup was measured by placing a 12-inch, plastic triangle across the face of the board and measuring maximum deviation. The total number of surface checks, end checks, and end splits was counted on each board. Any indications of honeycombing or collapse were noted, and several boards from each charge were tested for case-hardening (Rasmussen 1961).

Climatic Data—Daily solar radiation and hourly ambient temperature and humidity conditions were monitored just outside the solar kiln. Additionally, sky cover, temperature, wet-bulb temperature, relative humidity, and wind speed data at 3-hour intervals were obtained from the National Weather Service Station at Ryan Airport in Baton Rouge.

Results

The solar kiln was tested with six charges of wood between March, 1978 and January, 1979. Drying data was collected for all four seasons, and all 12 months except February, July, and September. The kiln was tested under optimal as well as poor climatic conditions. Table 4 summarizes the kiln and external ambient drying conditions during the experiment. Overall, the kiln maintained an average temperature of 97.6°F which was 30.5°F over average ambient of 67.1°F. The average volume of lumber dried was approximately 300 bd-ft, making the average S/L ratio equal to 0.088 ft^2/bd-ft. Solar- and air-drying times of each load to various moisture contents are given in Table 5.

The quality of the seasoned lumber from all six loads is summarized in Table 6. The average green moisture content of these 294 boards was 73.6 percent; the average moisture content after seasoning was 10.8 percent. Bow, crook, and twist of the boards averaged less than 1 percent of length, and cup averaged 1.3 percent of width. The average board had 3.1 surface checks and less than one end check or end split. Analysis of variance showed species to be the most significant independent variable in the analysis, but pith location was also a large source of drying defects, especially checking and splitting (Table 7).

Drying Charge 1 (8/4 Ash)

Kiln and ambient temperature and relative humidity parameters during the drying period are shown in Table 8, and graphically presented in Figure

Table 4.—Summary of climatic conditions inside and outside of solar kiln

Drying period	Lumber	Volume	S/L Ratio[1]	Mean temperature			Mean rel. humidity		EMC
				Kiln	Ambient	Diff.	Kiln	Ambient	
		(Bd-ft)		......	(^{o}F)	....	......	(%)	(%)
3/22 - 4/10/78	8/4 Ash	360	.073	102.3	66.0	36.3	53.6	68.5	9.3
4/22 - 5/12/78	8/4 Hackberry	352	.075	103.5	72.0	31.5	--[2]	71.7	--[2]
5/18 - 6/16/78	6/4 Red oak	265	.099	114.2	79.4	34.8	41.3	77.3	7.1
8/3 - 8/23/78	4/4 Ash	270	.097	110.7	85.9	24.8	54.5	78.7	9.6
10/6 - 10/27/78	4/4 Cypress	265	.099	96.4	67.6	28.8	55.5	70.5	10.4
11/11/78 - 1/11/79	6/4 Red oak	265	.099	82.2	53.8	28.4	63.0	61.4	12.3
Average:		297	.088	97.6	67.1	30.5	44.5	74.5	12.6

[1]Ratio of solar collector glazing area to lumber capacity.

[2]Data missing due to instrument failure.

Table 5.—Solar and air drying times to reach certain moisture contents (MC) for various species

Lumber	Drying period	Initial MC	Drying time: Solar 30%MC	Drying time: Solar 20%MC	Drying time: Solar 15%MC	Drying time: Air 30%MC	Drying time: Air 20%MC
		(%)	....	....	(Days)	....	....
8/4 Ash	3/22 - 4/10/78	51	6	13	18	16	(47)[1]
8/4 Hackberry	4/22 - 5/12/78	81	10	15	19	24	(50)[2]
6/4 Red oak	5/18 - 6/16/78	82	16	25	29	51	(104)[3]
4/4 Ash	8/3 - 8/23/78	50	3	6	9	7	22
4/4 Cypress	10/6 - 10/27/78	89	8	12	14	16	27
4/4 So. pine		160	6	7	8	12	23
6/4 Red oak	11/11/78 - 1/11/79	92	35	55	(66)[4]	112	--
4/4 So. pine		111	9	11	15	25	43

[1] Estimated by extrapolation. Drying stopped at 22% MC after 41 days.
[2] Estimated by extrapolation. Drying stopped at 22% MC after 45 days.
[3] Estimated by extrapolation. Drying stopped at 23% MC after 88 days.
[4] Estimated by extrapolation. Drying stopped at 17% MC after 62 days.

Table 6.—Summary of characteristics of lumber quality for all drying charges

Characteristic	Species[1]						Overall
	Ash	Hack-berry	Red oak	Ash	Cypress	Red oak	
Thickness (inch)	8/4	8/4	6/4	4/4	4/4	4/4	--
Green MC (%)	48.5	84.6	77.0	50.5	101.2	90.1	73.6
Dried MC (%)	12.3	13.6	15.4	6.8	7.2	14.1	10.8
Drying time (days)	19	20	29	20	21	62	28.5
Number of knots	6.8	6.4	15.1	3.4	3.8	3.0	5.9
Bow (1/32-inch)	6.7	12.4	5.9	5.6	4.5	4.4	6.4
Crook (1/32-inch)	6.8	13.8	4.5	6.6	5.5	9.0	7.4
Twist (1/32-inch)	5.8	6.0	2.9	5.5	6.6	14.2	6.7
Cup (1/32-inch)	2.1	5.3	5.7	1.7	2.2	4.4	3.3
Surface checks[2]	0.0	0.7	15.6	0.2	1.5	4.3	3.1
End checks[2]	0.5	0.4	4.6	0.0	0.0	0.7	0.9
End splits[2]	1.0	0.5	0.8	0.2	0.2	0.5	0.5

[1]All were No. 2 Common grade except 4/4 ash which was No. 3 Common.

[2]Based on total number of checks on each board.

Table 7.—Effect of position in kiln, pith location, knots, and species on moisture contents and drying defects in six kiln charges

Dependent variables	Independent variables				
	Row[1]	Column[2]	Pith location	No. of knots	Species
Green MC	NS	***	***	NS	***
Dried MC	***	NS	***	***	***
Bow	*	NS	NS	NS	***
Crook	***	NS	*	NS	***
Twist	***	NS	***	*	***
Cup	***	**	***	**	***
Surface checks	**	NS	***	***	***
End checks	***	NS	***	***	***
End splits	NS	NS	***	NS	NS

[1]Row refers to horizontal layers in the lumber pile. It is important to the extent that loading (weight) affects warping.

[2]Column refers to vertical layers in the lumber pile. It is important to the extent that relationship to the fan (heat source) affects drying rate.

NS = Not significant

* $P < .05$

** $P < .01$

*** $P < .001$

6. Average kiln temperature was 102°F and average relative humidity was 53.6 percent. The drying run indicated that the solar kiln performed very well. Its temperature was always above external ambient except during the first hours of operation, and the average humidity was lower than ambient. Weather was favorable during most of the drying period; there were many sunny days and average ambient temperature was slightly above normal.[7] As drying progressed kiln temperature showed a general upward trend due to thermal storage in the wood pile and less evaporative cooling by the lumber. Kiln and ambient temperatures both showed diurnal fluctuations, but the kiln had a lower coefficient of variation (9.6 vs. 16.2) indicating that it was more temperature stable than external ambient. Likewise, the relative humidity of the kiln (CV = 23.3) seemed to be more stable than that of the ambient humidity (CV = 27.9). The average temperature difference between kiln and ambient was 36.3°F. The average equilibrium moisture content of wood in the kiln was 9.3 percent, lower than could be

[7]Normal as established by National Oceanic and Atmospheric Administration (1976).

Table 8.—Climatic properties inside and outside of solar kiln during Charge 1

Property	N[1]	Mean	Standard deviation	Range
Dry bulb kiln temp (°F)	456	102.3	9.8	66.0 - 123.0
Wet bulb kiln temp (°F)	456	86.4	9.3	64.0 - 106.0
Humidity inside kiln (%)	456	53.6	12.5	32.0 - 91.0
Equilibrium MC of wood (%)	456	9.3	2.8	6.1 - 20.7
Ambient temp (°F), campus[2]	456	66.0	10.7	38.0 - 87.0
Ambient temp (°F), airport[3]	151	65.2	10.4	39.0 - 83.0
Ambient humidity (%), airport	151	68.5	19.2	26.0 - 100.0
Temp difference (kiln-ambient, °F)	456	36.3	8.7	-2.0 - 50.0
Blackbody temp (°F)	456	85.1	23.7	44.0 - 144.0
Cloud cover (1/10's)	151	5.4	7.7	0.0 - 10.0
Wind speed (mph)	151	7.6	4.2	0.0 - 16.1

[1] N refers to number of measurements.
[2] Ambient temperature was measured outside the solar kiln.
[3] Ambient temperature was measured at the Greater Baton Rouge Airport.

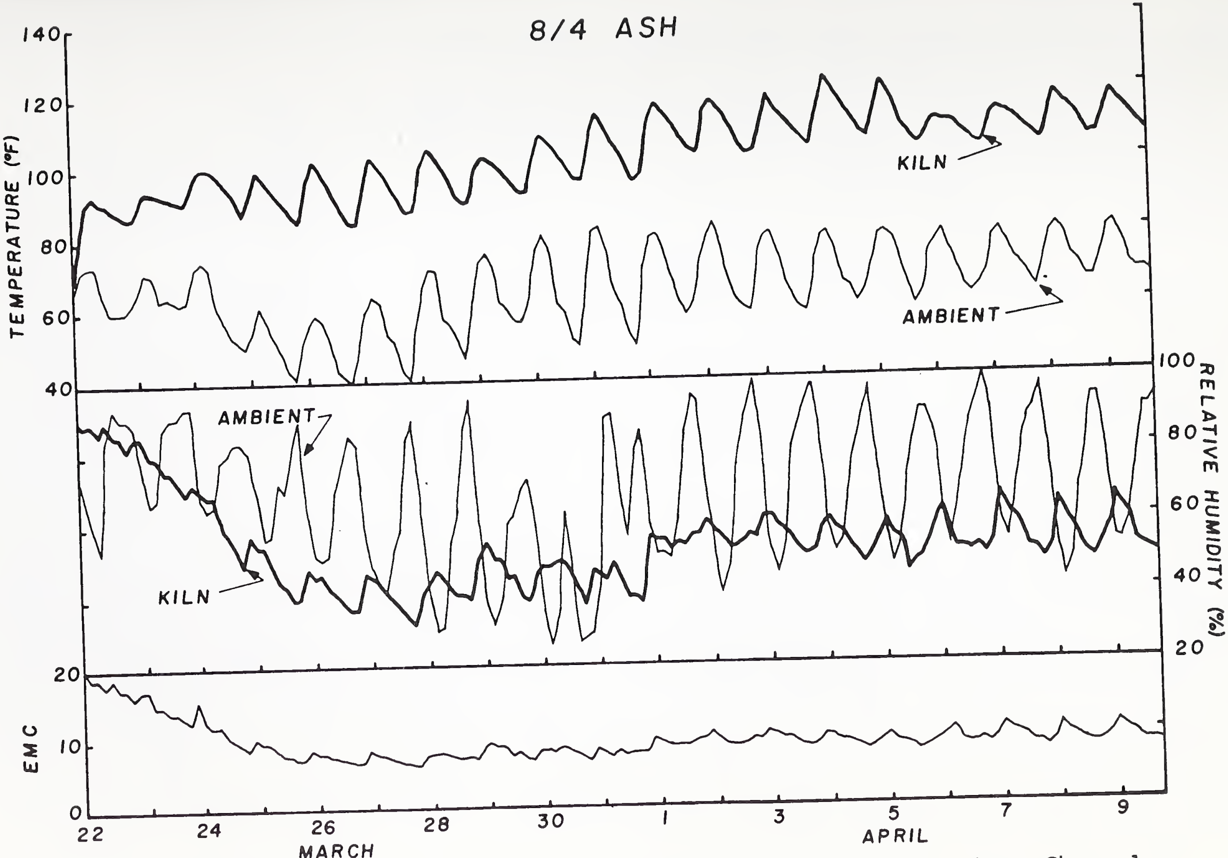

Figure 6.—Diurnal temperature, relative humidity, and EMC fluctuations during Charge 1.

expected in air drying.

The mean green moisture content of the kiln samples was 51.3 percent, while that of the air samples was 47.6 percent. In comparison with air drying, the kiln samples dried at a much faster rate, especially in the latter stages, and reached a lower final moisture content. As shown in Figure 7, the kiln samples dried from a mean 51.3 percent MC to 14.4 percent in 19 days. whereas the air samples dried to 29.6 percent MC in 19 days and to 22.3 percent in 40 days. The drying rates slowed down considerably during the latter stages so the load was removed from the kiln. The lumber could have been finished efficiently in a standard dry kiln faster since it had dried to the point where it could have tolerated more drastic drying conditions.

The drying characteristics of the boards are summarized in Table 9. The mean moisture content after drying was 12.3 percent, with a standard deviation of 1.21. The dried moisture contents of the kiln samples were not significantly different. The lower coefficient of variation for dried moisture content, as compared with the green moisture content (9.9 vs. 14.0, respectively), indicates convergence toward an equilibrium during drying. Analysis of variance showed that pith location, used as an indicator for lumber quality, significantly affected drying degrade (Table 10). Large knots seemed to be associated with much of the warping defect. This was, however, not detected by analysis of variance, possibly because the data did not consider the size of knots but only the number of knots shown on both faces. No evidence of collapse or honeycombing was noticeable in any of the boards. Slight case-hardening was detected, but the data were not subjected to numerical analysis. Bow, crook, and twist averaged 0.29, 0.30, and 0.25 percent of length, respectively. Cup averaged 0.82 percent of width. The significant effects of pith location on crook, cup, twist, end checks, and surface checks could be expected from the low strength and lack of dimensional stability in juvenile wood.

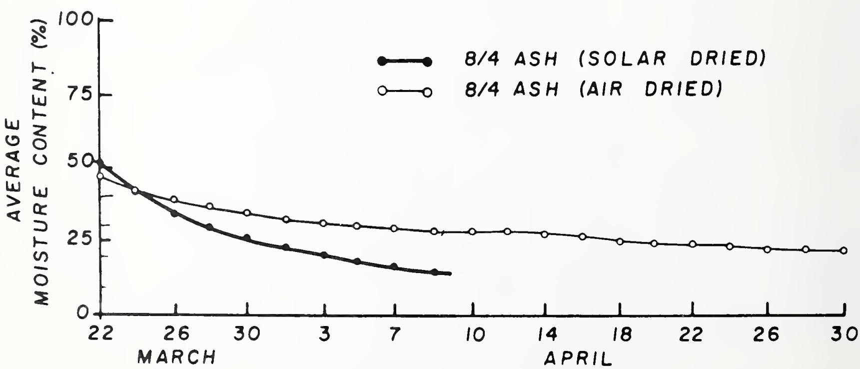

Figure 7.—Solar and air drying rates during Charge 1.

Table 9.—Characteristics of lumber quality in Charge 1 (8/4 No. 2 ash)

Characteristic	N	Mean	Standard deviation	Range
Green MC (%)	46	48.5	6.8	21.3 - 74.5
Dried MC (%)	46	12.3	1.2	6.5 - 14.1
Number of knots	46	6.8	3.3	0.0 - 17.0
Bow (1/32-inch)	46	6.7	3.2	2.0 - 16.0
Crook (1/32-inch)	46	6.8	3.9	0.0 - 16.0
Twist (1/32-inch)	46	5.8	4.1	0.0 - 16.0
Cup (1/32-inch)	46	2.1	1.1	0.0 - 5.0
Surface checks	46	0.0	0.0	0.0 - 0.0
End checks	46	0.5	0.9	0.0 - 3.0
End splits	46	1.0	1.2	0.0 - 4.0

Table 10.—Effect of position in kiln, pith location, and knots on moisture contents and drying defects of Charge 1

Dependent variables	Independent variables			
	Row	Column	Pith location	No. of knots
Green MC	NS	NS	NS	NS
Dried MC	*	NS	NS	NS
Bow	NS	NS	NS	NS
Crook	NS	*	*	NS
Twist	NS	NS	NS	NS
Cup	NS	NS	**	NS
Surface checks	--[1]	--	--	--
End checks	*	NS	**	NS
End splits	NS	NS	***	NS

[1]No surface checking was observed.

Differences in moisture contents among row positions in the kiln indicate some deficiencies in the air circulation system, especially since green moisture contents were not significantly different. Reversing the direction of air flow might minimize this effect.

Drying Charge 2 (8/4 Hackberry)

Failure of the electronic psychrometer assembly during this test limited interpretation of drying conditions because of the absence of relative humidity and equilibrium moisture content data. The average ambient temperature during the period was about normal. The mean kiln temperature was slightly higher (103.5°F) than the previous load (Table 11), but the average temperature difference (31.5°F) between kiln and ambient was lower, probably due to higher ambient temperatures, higher initial wood moisture content, and two periods of cloudy and rainy weather. These periods (May 3 and May 6-8), as indicated in Figure 8, had very high ambient relative humidity and lower-than-normal kiln temperature. It should be noted that the kiln maintained a temperature of 100°F or more during these periods with little or no solar heat input, which demonstrates the kiln's ability to store heat. Divergence from the normal pattern on April 23-24 was due to fan failure, resulting in high blackbody temperature of

Table 11.—Climatic properties inside and outside of solar kiln during Charge 2

Property	N	Mean	Standard deviation	Range
Dry bulb kiln temp (°F)	485	103.5	10.6	72.0 - 127.0
Wet bulb kiln temp (°F)	---[1]	--	--	-- --
Humidity inside kiln (%)	---[1]	--	--	-- --
Equilibrium MC of wood (%)	---[1]	--	--	-- --
Ambient temp (°F), campus	484	72.0	8.7	50.0 - 92.0
Ambient temp (°F), airport	162	70.7	8.4	49.0 - 86.0
Ambient humidity (%), airport	162	71.7	18.3	27.0 - 97.0
Temp difference (kiln-ambient, °F)	484	31.5	10.4	-6.0 - 50.0
Blackbody temp (°F)	484	99.5	20.7	57.0 - 210.0[2]
Cloud cover (1/10's)	162	5.9	4.3	0.0 - 10.0
Wind speed (mph)	162	9.6	4.4	0.0 - 23.0

[1]Data are not available due to failure of wet bulb sensing unit.
[2]Extreme value to to fan failure.

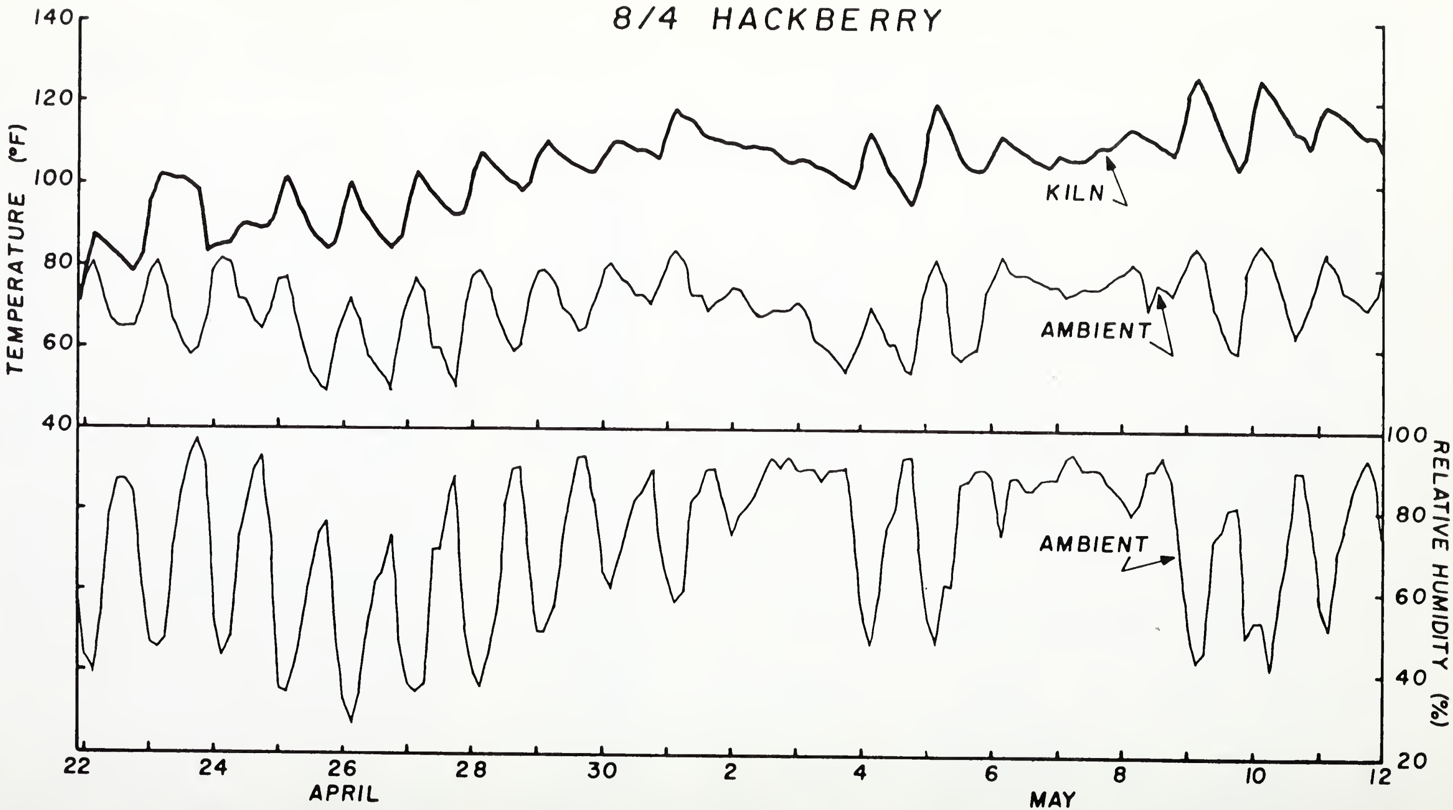

Figure 8.—Diurnal temperature and relative humidity fluctuations during Charge 2.

210.0°F. As in the previous load, a negative temperature difference between kiln and ambient (−6°F) occurred immediately after the kiln was loaded.

The average green moisture content of the kiln samples was 80.9 percent, whereas that of the air samples was 80.2 percent. Drying curves for solar and air drying, shown in Figure 9, indicate that it took 20 days for the kiln samples to dry from 81 percent to 13.5 percent MC, whereas the air samples reached only 33.6 percent MC during the same period.

The air samples dried faster than the kiln samples during the first 5 days but much slower after that, suggesting that there was insufficient potential for evaporation when high humidities were present in the initial kiln stages despite the increased temperature. To minimize this effect, one could partially dry high moisture content lumber to about 50 percent MC, which is the point where solar drying seemed to overtake air drying in hackberry. Another alternative may be to vent the solar kiln in the initial stages to increase evaporative capacity, especially if the wood is not refractory.

Drying characteristics of the load are summarized in Table 12. Analysis of variance showed twist was significantly affected by knots, and checking was related to pith location and kiln position (Table 13). Warping was about twice as severe as that of the previous load, despite the similar size and drying conditions of the boards. The reason may be due to hackberry's low dimensional stability. Mean bow, crook, and twist were 0.54, 0.60, and 0.26 percent of length, respectively. Average cupping was 2.07 percent of width. No evidence of collapse or honeycombing was noted, but some slight casehardening was detected.

The significant effect of pith location on checking could be expected for the same reasons utlined for the previous load. Cross grains in knots contribute to warping defects. The significant effect of column position in the kiln on surface checking may be related to proximity to the fan. The

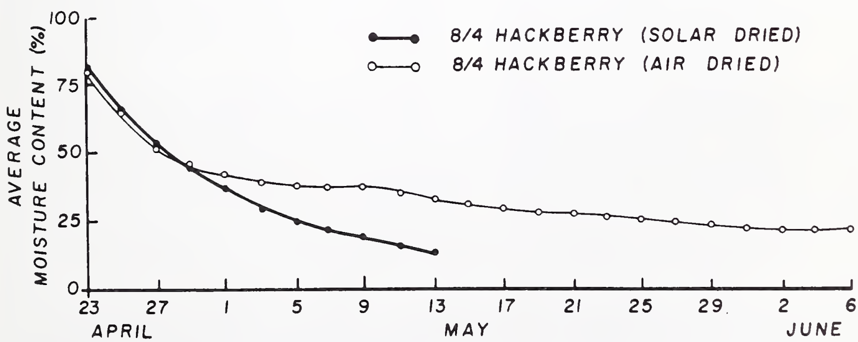

Figure 9.—Solar and air drying rates during Charge 2.

Table 12.—Characteristics of lumber quality in Charge 2 (8/4 No. 2 hackberry)

Characteristic	N	Mean	Standard deviation	Range
Green MC (%)	40	84.6	11.8	64.3 - 109.1
Dried MC (%)	40	13.6	2.5	8.5 - 17.8
Number of knots	40	6.4	4.9	0.0 - 17.0
Bow (1/32-inch)	40	12.4	8.6	4.0 - 44.0
Crook (1/32-inch)	40	13.8	9.8	3.0 - 43.0
Tiwst (1/32-inch)	40	6.0	4.9	0.0 - 20.0
Cup (1/32-inch)	40	5.3	1.3	3.0 - 9.0
Surface checks	40	0.7	1.2	0.0 - 5.0
End checks	40	0.4	0.8	0.0 - 3.0
End splits	40	0.5	0.8	0.0 - 2.0

Table 13.—Effect of position in kiln, pith location, and knots on moisture contents and drying defects of Charge 2

Dependent variables	Independent variables			
	Row	Column	Pith location	No. of knots
Green MC	NS	NS	NS	NS
Dried MC	NS	NS	NS	NS
Bow	NS	NS	NS	NS
Crook	NS	NS	NS	NS
Twist	NS	NS	NS	*
Cup	NS	NS	NS	NS
Surface checks	NS	*	**	NS
End checks	NS	NS	*	NS
End splits	NS	NS	NS	NS

boards in column one were the first to receive heated air. They were therefore subject to somewhat more severe drying conditions than columns two, three, and four which received air that had been slightly cooled and humidified by previous columns.

Drying Charge 3 (6/4 Red Oak)

Installation of a solar insolation integrator allowed measurement of the solar energy input onto the kiln. Mean daily solar radiation of 1,828.4 Btu/ft^2 (494.9 Langleys) was slightly higher than average insolation in New Orleans but slightly less than average in Lake Charles or Shreveport for the period (Table 1). Solar kiln and ambient temperature and humidity parameters are summaried in Table 14. The drying conditions reflect the harshness of Louisiana summers. Average temperature in the kiln was over 114°F, which is a good deal above average ambient (79.4°F) and was highest of all drying loads, whereas the average relative humidity (41.3 percent) was the lowest. Such conditions resulted in rather drastic drying and the load attained the lowest moisture equilibrium in the study—7.1 percent.

Figure 10 shows an upward trend in temperature and a downward trend in relative humidity as drying progresses. It also demonstrates the effects of 2 days (i.e. June 3 and 6) with little solar insolation. Neither kiln nor external ambient temperature made the usual peak at mid-afternoon, but due to good insulation and high heat storage capacity of wood, the kiln maintained a rather high temperature (over 100°F) without external heat input. Increases in ambient humidity were typical during these rainy periods. Slight increases in kiln humidity indicate that the wood was still drying despite unfavorable climatic conditions.

Even though the drying conditions were harsh, the drying rate was actually slower than previous loads because red oak is a refractory wood and difficult to dry. The average green moisture content was 81.8 percent for the kiln samples and 84.8 percent for the air samples. The kiln samples consistently dried more rapidly than the air samples, especially toward the latter stages of drying. They dried to 16.8 percent MC in 29 days, but the air samples only reached 42.0 percent in that period. After 91 days, the air samples had dried to an average 21.6 percent MC (Figure 11). Even though equilibrium was not yet reached, kiln drying was terminated at 15.4 percent MC.

The quality of drying is presented in Table 15. Surface checking was more pronounced in this load, as was end checking, probably because of harsher drying conditions and inherent characteristics of the species. Bow, crook, and twist were the lowest thus far at 0.26, 0.20, and 0.13 percent of length, respectively. Cupping, however, was most severe at 2.23 percent of width. No collapse or honeycombing was noted. Casehardening was moderate.

Analysis of variance (Table 16) showed significant relationships between dried moisture content and row and column position in the kiln, pith location, and number of knots. The row and column classes probably

Table 14.—Climatic properties inside and outside of solar kiln during Charge 3

Property	N	Mean	Standard deviation	Range
Dry bulb kiln temp ($^{\circ}$F)	696	114.2	8.1	86.0 - 132.0
Wet bulb kiln temp ($^{\circ}$F)	696	89.9	3.3	81.0 - 99.0
Humidity inside kiln (%)	696	41.3	13.3	21.0 - 85.0
Equilibrium MC of wood (%)	696	7.1	2.4	3.8 - 17.2
Ambient temp ($^{\circ}$F), campus	696	79.4	7.3	67.0 - 99.0
Ambient temp ($^{\circ}$F), airport	235	79.1	6.9	61.0 - 94.0
Ambient humidity (%), airport	235	77.3	15.7	43.0 - 100.0
Temp difference (kiln-ambient, $^{\circ}$F)	696	34.8	9.3	2.0 - 54.0
Blackbody temp ($^{\circ}$F)	696	97.9	19.6	74.0 - 146.0
Cloud cover (1/10's)	235	5.1	3.6	0.0 - 10.0
Wind speed (mph)	235	5.6	3.1	0.0 - 18.4
Daily insolation (Btu/ft^2)	29	1,828.4	452.9	455.0 - 2,460.0

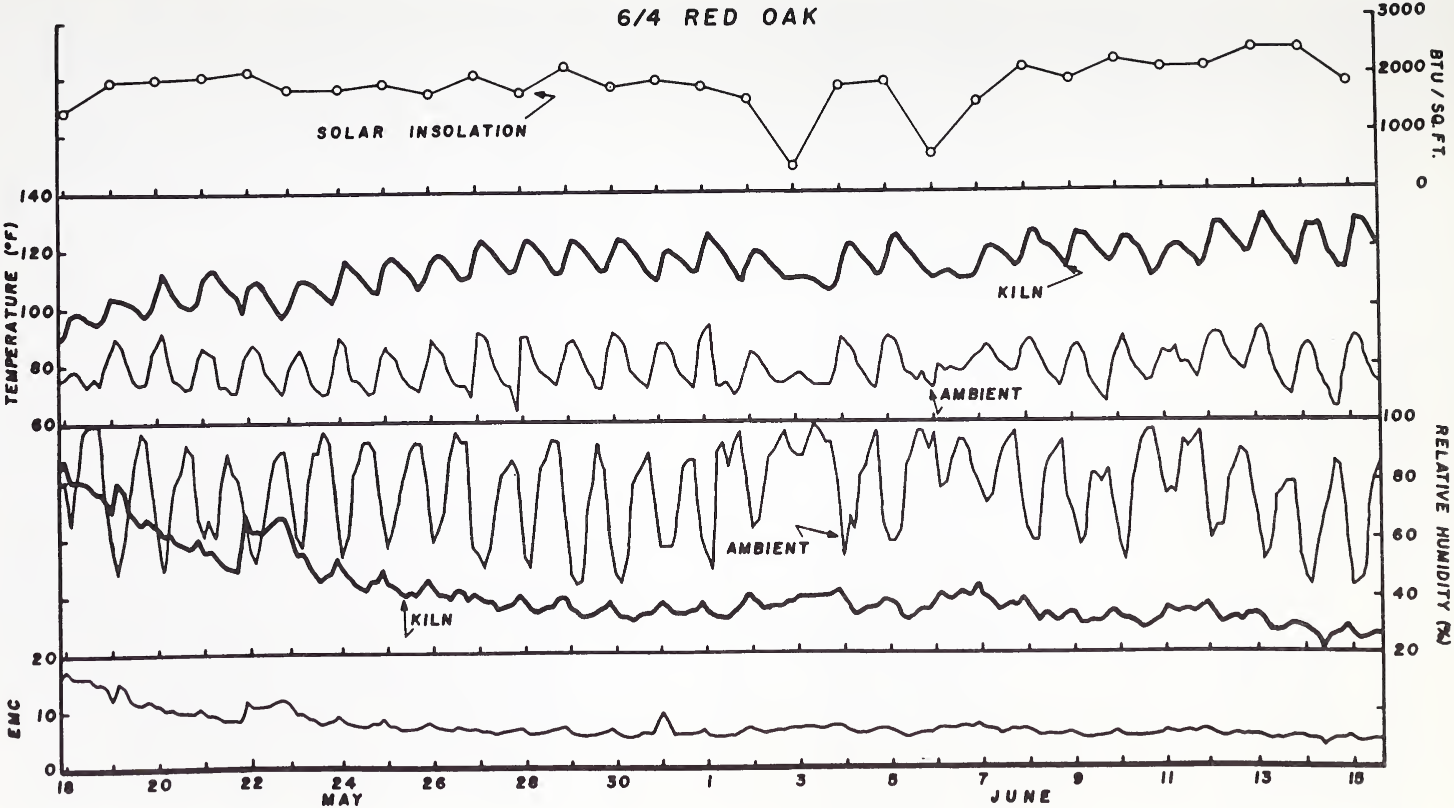

Figure 10.—Diurnal temperature, relative humidity, and EMC fluctuations during Charge 3.

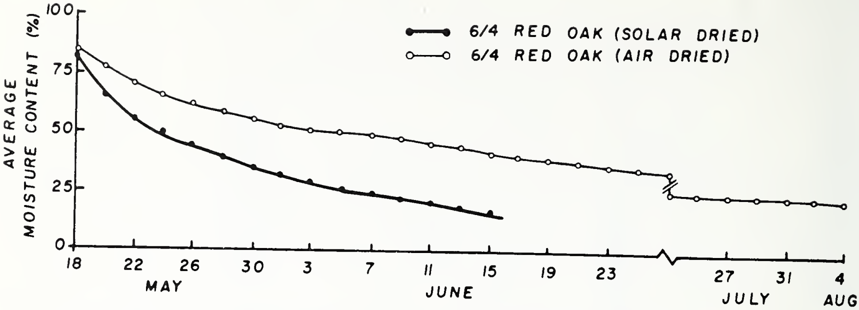

Figure 11.—Solar and air drying rates during Charge 3.

indicate inadequate air circulation. Pith location probably served as a proxy variable for heartwood/sapwood proportions. Boards with a higher percentage of sapwood seemed to have lower final moisture contents. The relationship between final moisture content and number of knots is not readily apparent but could be related to several phenomena such as sapwood/heartwood ratios and faster evaporation from end grain exposed by knots.

Table 15.—Characteristics of lumber quality in Charge 3 (6/4 No. 2 red oak)

Characteristic	N	Mean	Standard deviation	Range
Green MC (%)	40	77.0	9.4	58.8 - 93.7
Dried MC (%)	40	15.4	5.8	5.8 - 27.5
Number of knots	40	15.1	9.9	1.0 - 46.0
Bow (1/32-inch)	40	5.9	4.5	0.0 - 23.0
Crook (1/32-inch)	40	4.5	2.8	1.0 - 14.0
Twist (1/32-inch)	40	2.9	3.5	0.0 - 14.0
Cup (1/32-inch)	40	5.7	1.2	3.0 - 8.0
Surface checks	40	15.6	10.0	0.0 - 38.0
End checks	40	4.6	3.3	0.0 - 12.0
End splits	40	0.8	1.0	0.0 - 4.0

Table 16.—Effect of position in kiln, pith location, and knots on moisture contents and drying defects of Charge 3

Dependent variables	Independent variables			
	Row	Column	Pith location	No. of knots
Green MC	NS	NS	NS	NS
Dried MC	***	*	**	**
Bow	NS	NS	NS	NS
Crook	NS	NS	NS	NS
Twist	NS	NS	NS	NS
Cup	NS	NS	NS	NS
Surface checks	NS	NS	NS	NS
End checks	NS	NS	NS	NS
End splits	NS	NS	NS	NS

Drying Charge 4 (4/4 Ash)

This load of lumber was dried late in the summer when solar insolation had begun to taper off. An average of 1,645.1 Btu/day of heat energy was available to each square foot of solar collector. Once again, this value appears to be intermediate between the averages for New Orleans on the low side, and Lake Charles and Shreveport on the high side. The kiln maintained an average temperature of 110.7°F, which is slightly below the 114.2°F average set earlier in the summer (Table 17). The average temperature difference between kiln and ambient was 24.8°F. The average relative humidity in the kiln (54.5 percent) was considerably lower than that of the ambient environment (78.7 percent). Diurnal temperature and humidity fluctuations are shown in Figure 12.

The trend of rising temperature and falling humidity during drying occurred with the thinner lumber material as it did in previous loads. Equilibrium moisture content seemed to follow a pattern similar to relative humidity but was subject to slightly less variation. Diurnal temperature fluctuations were slightly higher, probably due to less lumber volume.

The average green moisture content was 49.9 percent for the kiln samples and 47.8 percent for the air samples. The kiln samples dried from the green condition to 6.7 percent MC in 20 days; whereas the matched air samples were able to reach 21.0 percent MC in that period and 16.4 percent

Table 17.—Climatic properties inside and outside of solar kiln during Charge 4

Property	N	Mean	Standard deviation	Range
Dry bulb kiln temp (^{o}F)	480	110.7	10.3	88.0 - 136.0
Wet bulb kiln temp (^{o}F)	480	92.9	4.9	82.0 - 106.0
Humidity inside kiln (%)	480	54.5	18.2	29.0 - 93.0
Equilibrium MC of wood (%)	480	9.6	4.2	4.9 - 21.2
Ambient temp (^{o}F), campus	480	85.9	7.7	71.0 - 98.0
Ambient temp (^{o}F), airport	158	80.3	6.5	69.0 - 96.0
Ambient humidity (%), airport	158	78.7	14.3	42.0 - 97.0
Temp difference (kiln-ambient, ^{o}F)	480	24.8	10.9	-5.0 - 49.0
Blackbody temp (^{o}F)	480	102.1	17.4	74.0 - 145.0
Cloud cover (1/10's)	158	5.0	3.6	0.0 - 10.0
Wind speed (mph)	158	5.3	3.3	0.0 - 17.2
Daily insolation (Btu/ft^2)	20	1,645.1	373.9	989.0 - 2,124.0

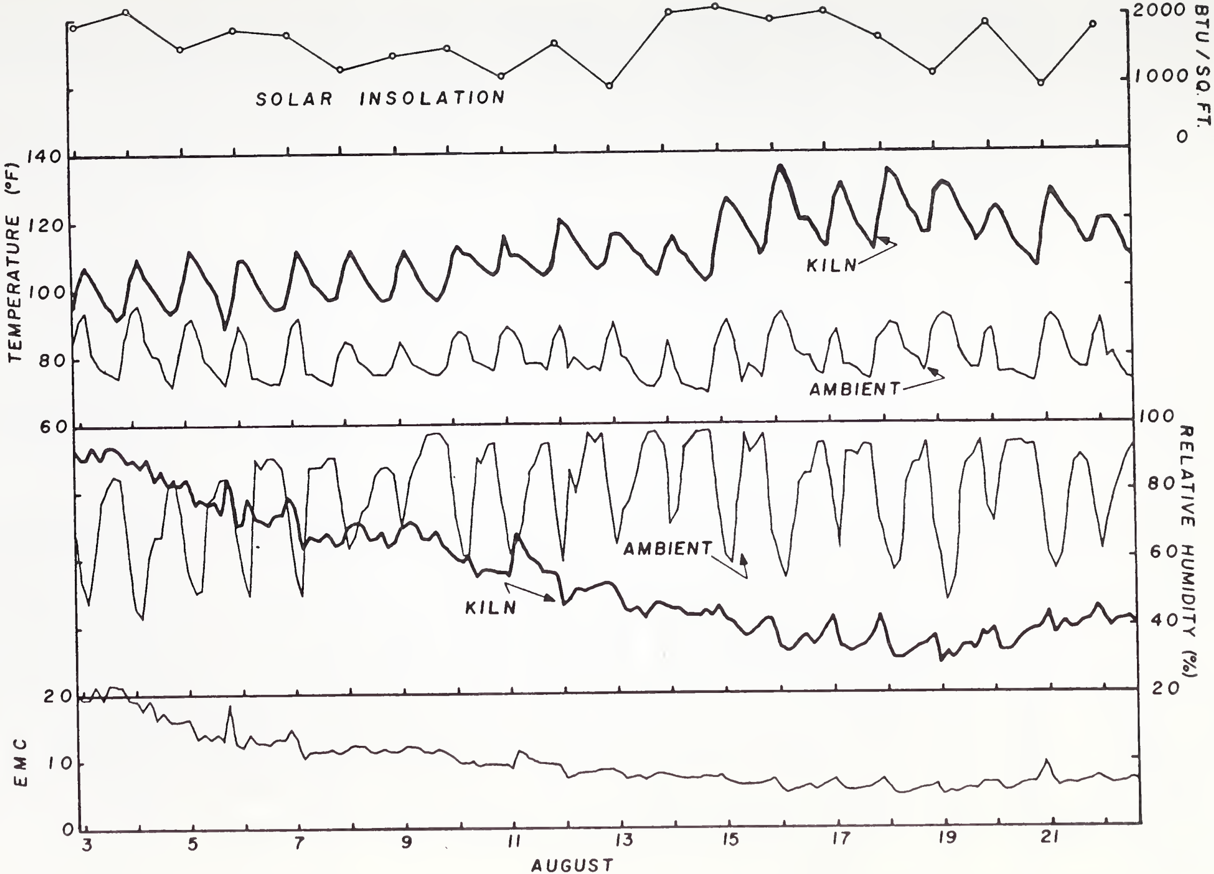

Figure 12.—Diurnal temperature, relative humidity, insolation and EMC fluctuations during Charge 4.

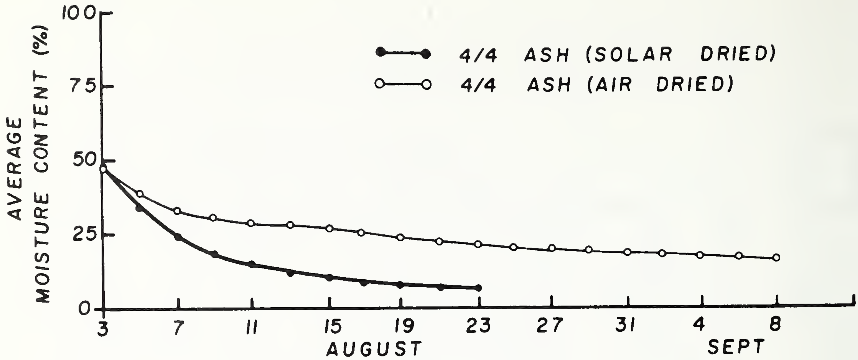

Figure 13.—Solar and air drying rates during Charge 4.

MC in 36 days (Figure 13). The final average moisture content for the kiln samples was 6.7 percent, and that of the charge was 6.8 percent. The coefficient of variation for the dried moisture content was 8.2, compared with 19.1 for the green moisture content, thus uniform drying was easily obtained with the thinner boards. The final moisture content was once again significantly affected by row position in the lumber pile. Drying rate was considerably faster for solar-dried boards than for the air-dried boards.

There was very little drying degrade in this load despite the poor quality (No. 3 Common) of the lumber material (Table 18). Analysis of variance showed that checking and splitting were highly significantly related to pith

Table 18.—Characteristics of lumber quality in Charge 4 (4/4 No. 3 ash)

Characteristic	N	Mean	Standard deviation	Range
Green MC (%)	71	50.5	9.6	21.3 - 80.7
Dried MC (%)	71	6.8	0.6	5.7 - 8.5
Number of knots	71	3.4	3.6	0.0 - 21.0
Bow (1/32-inch)	71	5.6	2.7	0.0 - 13.0
Crook (1/32-inch)	71	6.6	4.1	0.0 - 24.0
Twist (1/32-inch)	71	5.5	3.6	0.0 - 20.0
Cup (1/32-inch)	71	1.7	1.4	0.0 - 6.0
Surface checks	71	0.2	0.8	0.0 - 4.0
End checks	71	0.0	0.0	0.0 - 0.0
End splits	71	0.2	0.6	0.0 - 3.0

location (Table 19). The analysis also showed that final moisture content was highly significantly related to the row position in the lumber pile. Bow, crook, and twist were 0.24, 0.29, and 0.24 percent of length, respectively. Cup was only 0.66 percent of width. The low cup is probably due to thinner boards and excellent dimensional stability of ash. Surface checking and end-splitting were very low, and end-checking was non-existent. No collapse or honeycombing was found, and only slight casehardening developed.

Table 19.—Effect of position in kiln, pith location, and knots on moisture contents and drying defects of Charge 4

Dependent variables	Independent variables			
	Row	Column	Pith location	No. of knots
Green MC	NS	NS	NS	NS
Dried MC	**	NS	NS	NS
Bow	NS	NS	NS	NS
Crook	NS	NS	NS	NS
Twist	NS	NS	NS	NS
Cup	NS	NS	NS	NS
Surface checks	NS	NS	***	NS
End checks	--[1]	--	--	--
End splits	NS	NS	***	NS

[1]No end checks were observed.

Drying Charge 5 (4/4 Cypress)

Early fall is typically the sunniest season in Louisiana, and October was no exception. The average cloud cover of 24 percent was the lowest for all drying charges. Daily solar radiation averaged 1,482.5 Btu/ft^2 over the 21-day drying period. This is approximately equivalent to the average October solar insolation in Lake Charles but is higher than that of Shreveport or New Orleans. As shown in Table 20, the mean kiln temperature was 96.4°F, which was 28.8°F above average ambient (67.6°F). The

Table 20.—Climatic properties inside and outside of solar kiln during Charge 5

Property	N	Mean	Standard deviation	Range
Dry bulb kiln temp (^{o}F)	504	96.4	11.5	71.0 - 121.0
Wet bulb kiln temp (^{o}F)	504	81.0	6.5	66.0 - 98.0
Humidity inside kiln (%)	504	55.5	20.3	14.0 - 96.0
Equilibrium MC of wood (%)	504	10.4	4.8	2.7 - 24.0
Ambient temp (^{o}F), campus	504	67.6	7.7	50.0 - 87.0
Ambient temp (^{o}F), airport	170	64.9	10.3	42.0 - 86.0
Ambient humidity (%), airport	170	70.5	21.9	28.0 - 100.0
Temp difference (kiln-ambient,^{o}F)	504	28.8	9.5	2.0 - 47.0
Blackbody temp (^{o}F)	504	84.6	21.9	51.0 - 132.0
Cloud cover (1/10's)	170	2.4	3.4	0.0 - 10.0
Wind speed (mph)	170	5.4	4.1	0.0 - 19.6
Daily insolation (Btu/ft^2)	21	1,482.5	197.9	955.0 - 1,734.0

mean relative humidity in the kiln was 55.5 percent, while mean ambient was 70.5 percent.

Figure 14 illustrates the generally high level of solar insolation throughout the drying period. The previously recognized upward trend in kiln temperature and downward trend in kiln humidity is apparent. The graph also shows the extent of ambient humidity fluctuations even during a period of consistently clear and sunny weather. Contrast these with the comparatively small diurnal humidity fluctuations in the kiln. Equilibrium moisture content seemed to again follow kiln humidity rather closely.

The inclusion of southern pine samples in the charge allowed several interesting observations. The drying rate of the very permeable pine is exceptionally fast, even when compared to the relatively fast-drying cypress (Figure 15). The average green moisture content of the four cypress kiln samples was 88.4 percent while the air samples averaged 88.9 percent. The lumber dried very rapidly to 9.6 percent MC in 21 days in the solar kiln, whereas the matching air samples reached only 25.1 percent MC in that same time period and required 54 days to reach 18.9 percent MC. The southern pine kiln samples started from 160.4 percent MC and dried to 9.6 percent MC in 10 days and to 6.6 percent MC in 21 days. The pine air samples reached 48.6 percent MC in 10 days, 21.9 percent in 21 days, and 20.6 percent in 34 days.

The pine samples also demonstrate the difference in drying rate above and below the fiber saturation point, and indicate the need for more severe drying conditions during the latter stages. Since the pine samples made up a very small percentage of the total lumber volume, drying conditions were determined by the temperature/moisture interrelationships of the cypress. In previous loads, relative humidity in the kiln was reported to be directly related to wood moisture and inversely related to temperature. Assuming similar conditions existed in the cypress load, the pine had a comparative advantage in the initial drying stages. Because the humidity of the kiln was determined by the cypress at a lower moisture content, the pine initially had relatively more potential for evaporation. Once in the hygroscopic range though, the pine dried by a diffusion process, and the removal of moisture was slowed considerably by the mild drying conditions (i.e. lower temperature) caused by the wetter cypress lumber.

The quality of the seasoned lumber, shown in Table 21, was very good. Analysis of variance showed no significant effects of position in the kiln, pith location, or number of knots on the green moisture content, dried moisture content, or drying defects. No collapse or honeycombing was found, and only slight casehardening developed.

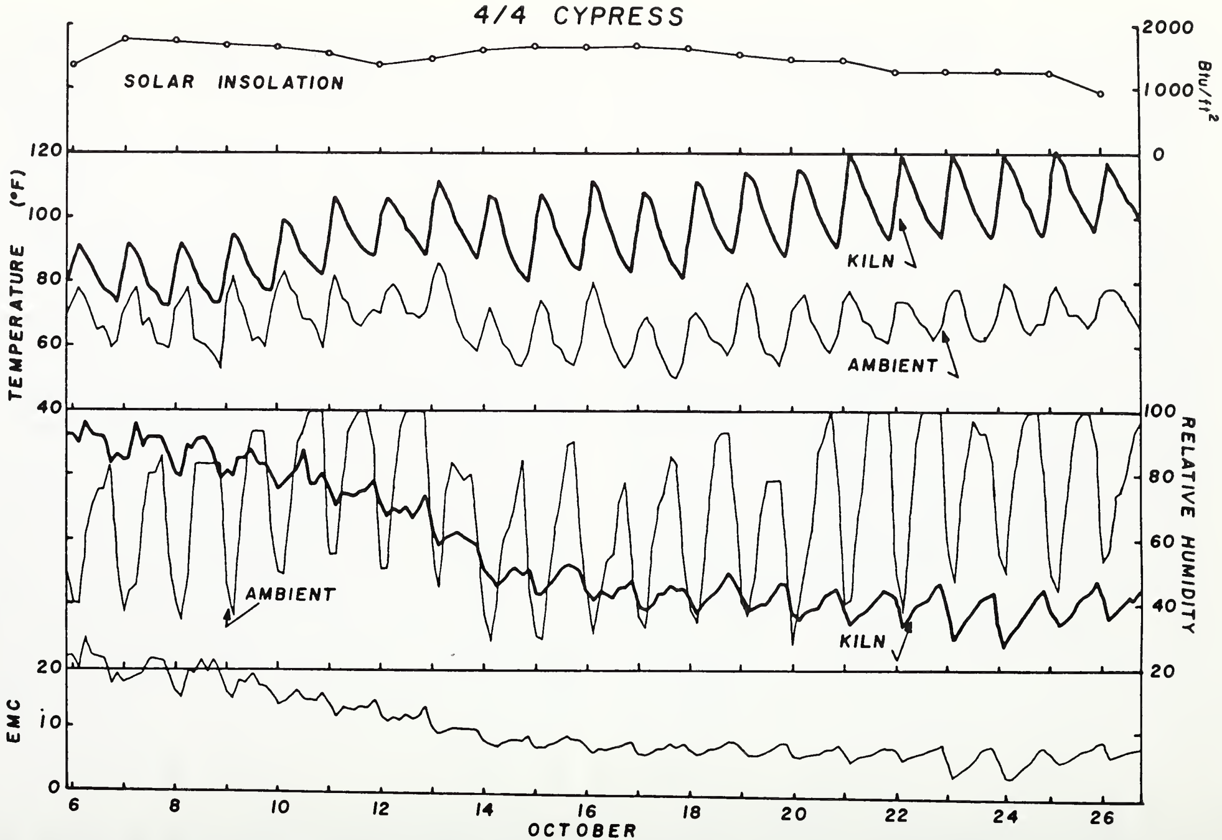

Figure 14.—Diurnal temperature, relative humidity, insolation, and EMC fluctuations during Charge 5.

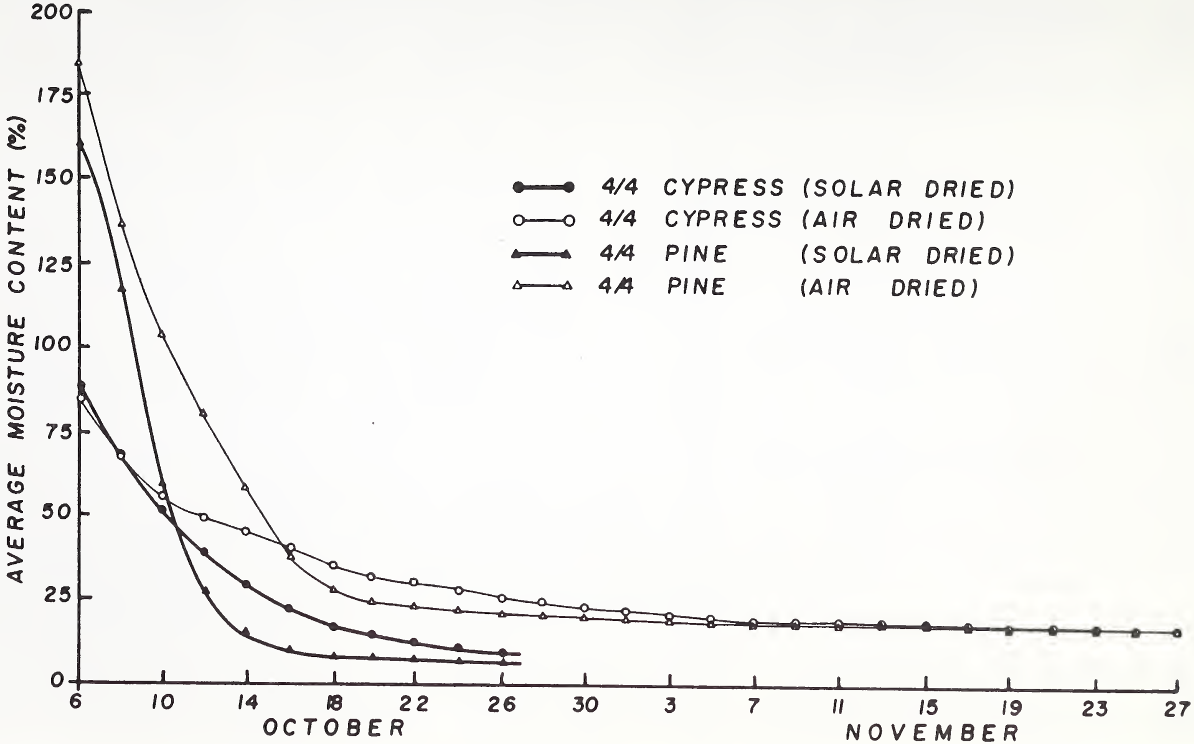

Figure 15.—Solar and air drying rates during Charge 5.

Table 21.—Characteristics of lumber quality in Charge 5 (4/4 No. 2 cypress)

Characteristic	N	Mean	Standard deviation	Range
Green MC (%)	56	101.2	25.8	51.5 - 147.4
Dried MC (%)	56	7.2	2.3	5.8 - 14.5
Number of knots	56	3.8	3.2	0.0 - 10.0
Bow (1/32-inch)	56	4.5	3.6	0.0 - 16.0
Crook (1/32-inch)	56	5.5	6.6	0.0 - 32.0
Twist (1/32-inch)	56	6.6	5.8	0.0 - 24.0
Cup (1/32-inch)	56	2.2	1.6	0.0 - 8.0
Surface checks	56	1.5	3.9	0.0 - 20.0
End checks	56	0.0	0.2	0.0 - 1.0
End splits	56	0.2	0.4	0.0 - 1.0

Drying Charge 6 (6/4 Red Oak)

The most severe test on the solar kiln was undertaken in the drying of a refractory red oak in the middle of the winter. The weather was cold, rainy and cloudy for the most part, with daily insolation averaging only 754.8 Btu/ft^2. This value is below the average for the period for Shreveport, Lake Charles, and New Orleans. The temperature of the kiln nudged above 100°F only 4 days and averaged only 82.2°F. It still averaged 28.4°F above ambient (Table 22). The temperature of the kiln (CV = 11.4) was more stable than the external ambient (CV = 25.8). The low temperatures during this period led to relatively high kiln humidities (average 63.0 percent) and equilibrium moisture contents (average 12.3 percent).

Figures 16a and 16b illustrate the relationships between solar insolation, ambient temperature and humidity, and drying conditions. Although the kiln was well insulated, its temperature seemed to follow the ambient temperature rather closely. This was partially due to air infusion during weight measurements, to leaks around the door during other periods, and to thermal leaks in places where insulation was as thick as desirable (i.e. near vents to the solar collector, at plumbing and electrical connections, etc). Kiln and ambient humidity do not seem to be directly related to each other, but may be indirectly related through the general level of solar radiation. Cloudy days typically had high humidities, usually caused by rain. The relative humidity in the kiln tended upward in these periods due to continued evaporation (i.e. increasing absolute humidity while simultaneously

Table 22.—Climatic properties inside and outside of solar kiln during Charge 6

Property	N	Mean	Standard deviation	Range
Dry bulb kiln temp (^{O}F)	1464	82.2	9.3	51.0 - 103.0
Wet bulb kiln temp (^{O}F)	1464	72.2	10.6	45.0 - 96.0
Humidity inside kiln (%)	1464	63.0	16.9	32.0 - 100.0
Equilibrium MC of wood (%)	1464	12.3	5.1	6.0 - 28.3
Ambient temp (^{O}F), campus	1464	53.8	13.9	22.0 - 79.0
Ambient temp (^{O}F), airport	157	63.2	8.8	46.0 - 80.0
Ambient humidity (%), airport	157	61.4	33.9	31.0 - 100.0
Temp difference (kiln-ambient, ^{O}F)	1464	28.5	8.8	7.0 - 54.0
Blackbody temp (^{O}F)	1464	60.1	28.3	24.0 - 116.0
Cloud cover (1/10's)	157	6.9	3.5	0.0 - 10.0
Wind speed (mph)	157	5.3	3.0	0.0 - 11.5
Daily insolation (Btu/ft^2)	61	754.8	344.1	133.0 - 1,210.0

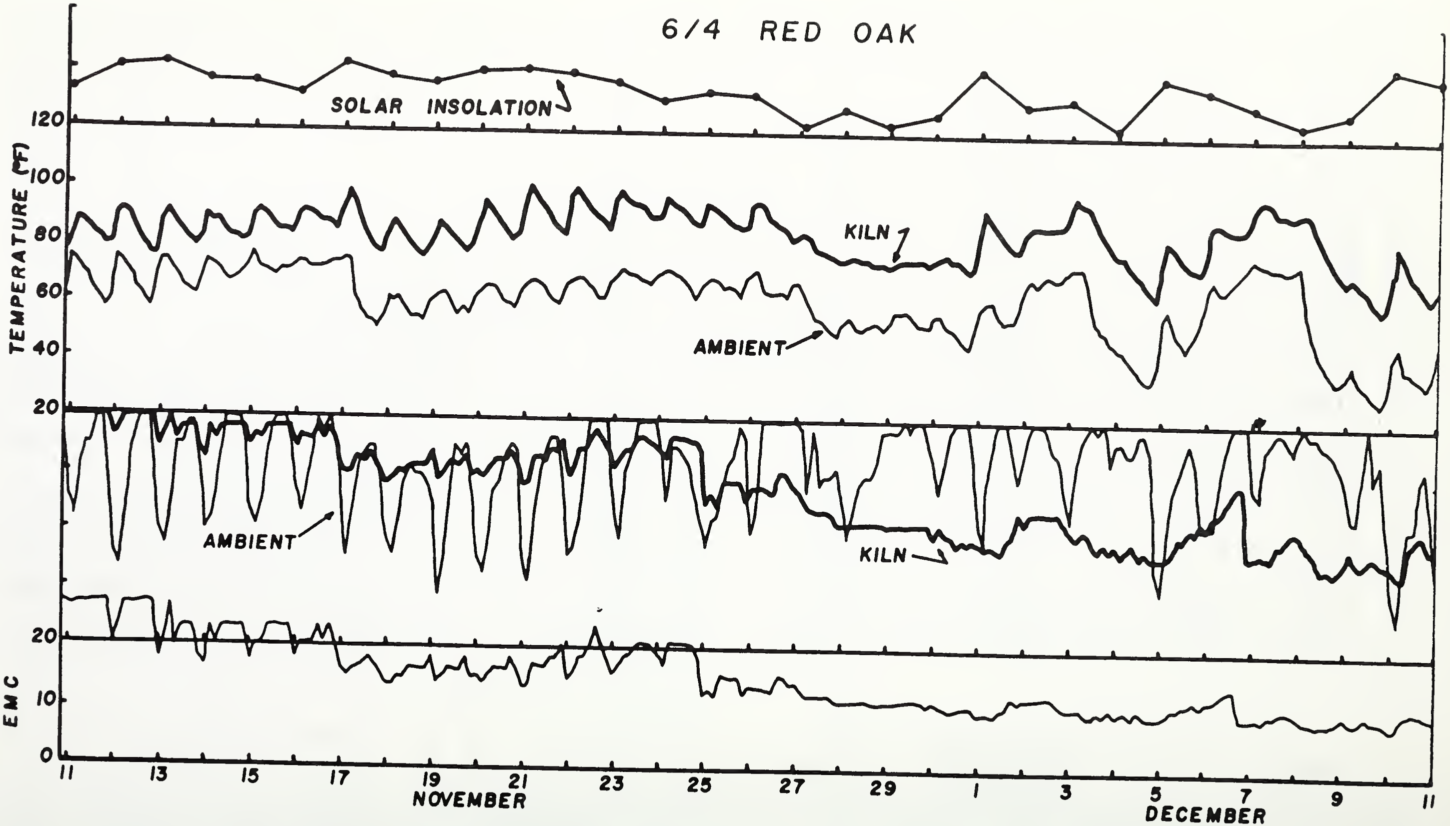

Figure 16a.—Diurnal temperature, relative humidity, and EMC fluctuations during Charge 6.

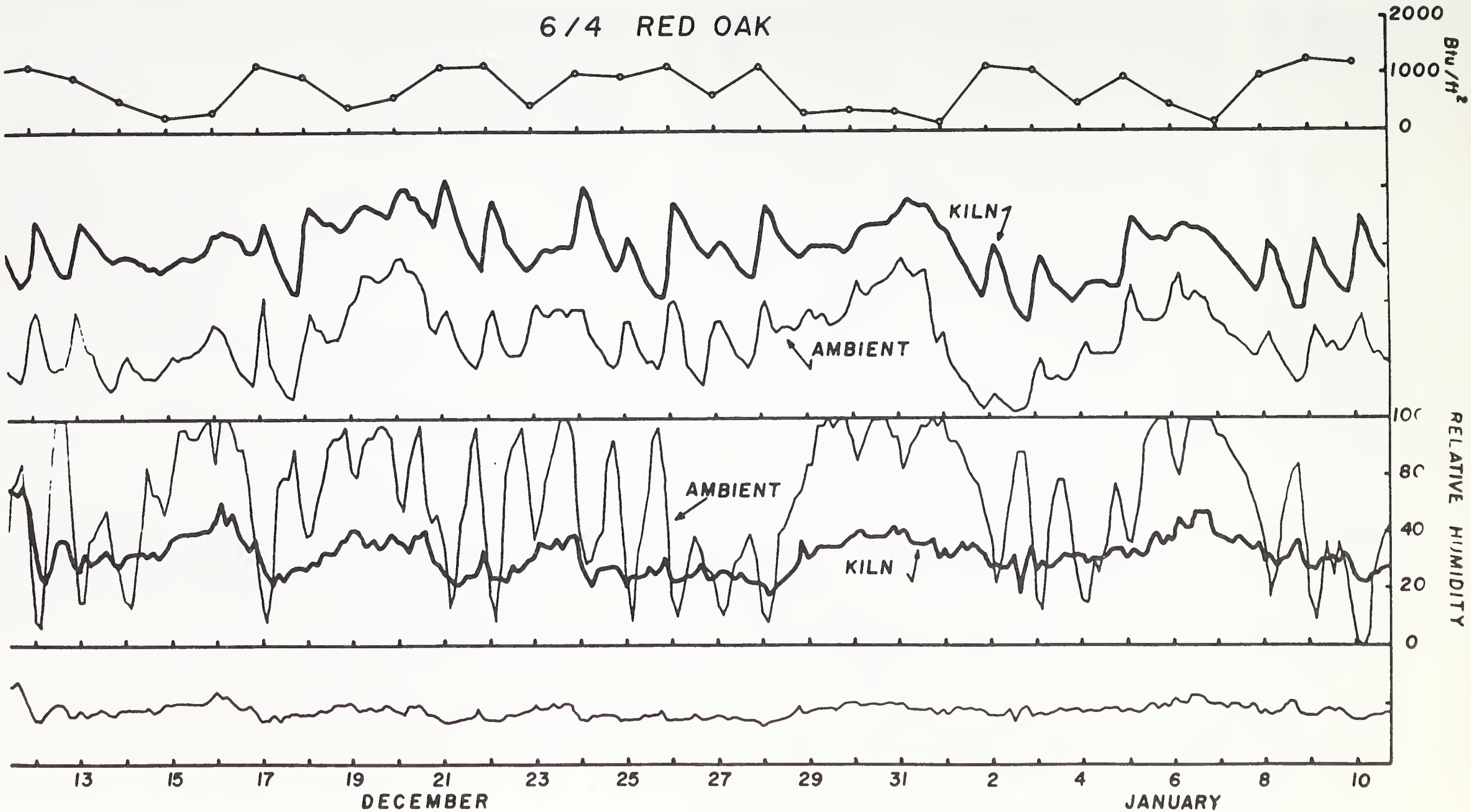

Figure 16b.—Diurnal temperature, relative humidity, and EMC fluctuations during Charge 6.

lowering temperatures) with little heat input. The equilibrium moisture content seems to follow kiln humidity closely. The typical upward trend in temperature is noticeable during some periods (November 11-26 and December 10-21) but an overall trend is masked by variability in solar insolation and ambient temperature.

Solar- and air-drying rates for the 6/4 red oak and the 8/4 southern pine are graphically depicted in Figure 17. The red oak dried considerably slower, with the kiln samples drying from 92.4 percent MC to 17.3 percent in 62 days and the air-dried samples reaching 29.8 percent MC in 112 days. After 62 days, the red oak had air-dried to only 37.5 percent MC. The southern pine kiln samples started from 111.0 percent MC and dried to 17.0 percent in approximately 13 days and to 9.0 percent in 62 days. The air-dried pine samples reached 37.0 percent MC in 21 days and 17.6 percent in 62 days. Even though the pine boards were thicker than the oak, the former dried faster and reached lower final moisture content.

The mild drying conditions had some favorable effects. As shown in Table 23, checking was considerably reduced from the level found in the red oak previously dried in the summer (which was also 6/4 thick). Casehardening was also less severe. The surface checking that was observed was significantly related to row position in the kiln and pith location. The relation to pith location probably stems from the weaker, dimensionally less stable wood near the pith. The relationship to row position probably indicates uneven air circulation in the kiln.

Bow, crook, and twist were 0.2, 0.4, and 0.6 percent of length, respectively, and cup was 1.7 percent of width. Analysis of variance showed that the row position in the lumber pile was a significant source of crook, twist, and surface checks (Table 24), indicating the need to restrain warping in small piles, possibly by using weights on top of the wood stack. No collapse or honeycombing was found, and only slight casehardening developed. Blue stain fungus developed on the pine air samples, but not on the oak samples because they had been treated with preservatives at the mill. The solar-dried pine samples dried fast enough in the kiln so that no blue stain developed even without preservative treatment.

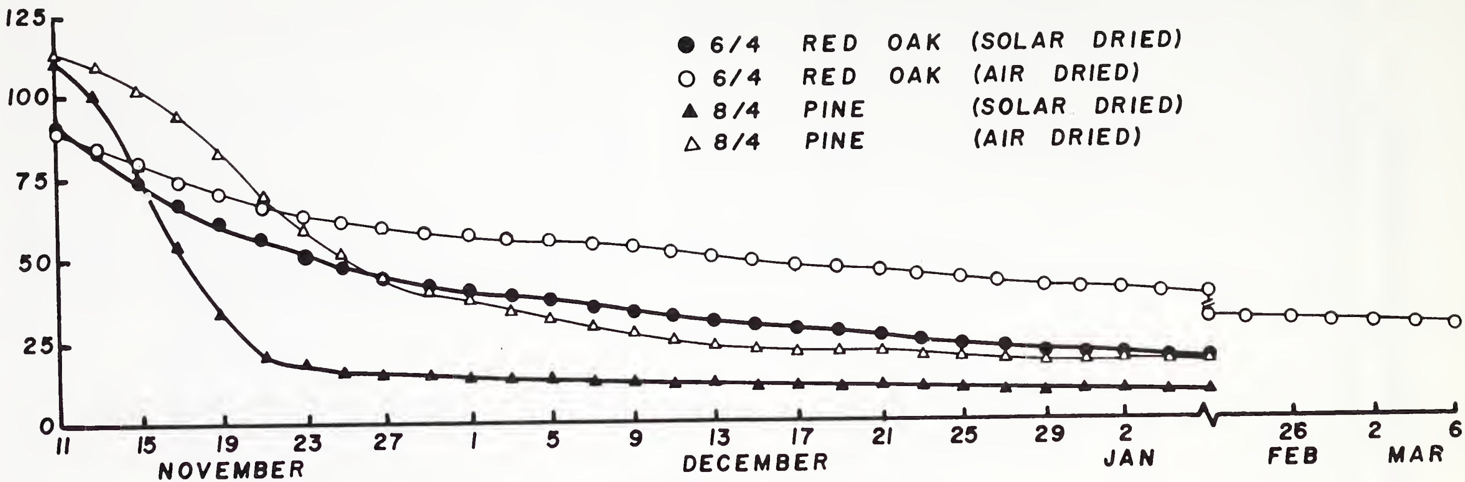

Figure 17.—Solar and air drying rates during Charge 6.

Table 23.—Characteristics of lumber quality in Charge 6 (6/4 No. 2 red oak)

Characteristic	N	Mean	Standard deviation	Range
Green MC (%)	41	90.1	7.4	78.0 - 107.1
Dried MC (%)	41	14.1	4.4	7.7 - 21.8
Number of knots	41	3.0	2.3	0.0 - 10.0
Bow (1/32-inch)	41	4.4	4.0	0.0 - 16.0
Crook (1/32-inch)	41	9.0	6.5	0.0 - 30.0
Twist (1/32-inch)	41	14.2	7.6	2.0 - 36.0
Cup (1/32-inch)	41	4.3	3.0	0.0 - 10.0
Surface checks	41	4.3	9.4	0.0 - 46.0
End checks	41	0.7	1.4	0.0 - 5.0
End splits	41	0.5	1.0	0.0 - 4.0

Table 24.—Effect of position in kiln, pith location, and knots on moisture contents and drying defects of Charge 6

Dependent variables	Independent variables			
	Row	Column	Pith location	No. of knots
Green MC	NS	NS	NS	NS
Dried MC	NS	NS	NS	NS
Bow	NS	NS	NS	NS
Crook	*	NS	NS	NS
Twist	*	NS	NS	NS
Cup	NS	NS	NS	NS
Surface checks	**	NS	**	NS
End checks	NS	NS	NS	NS
End splits	NS	NS	NS	NS

Discussion and Summary

To measure the effectiveness of a solar kiln one must not only measure output (i.e. heat rise above ambient) but input, the latter being defined as the amount of heat collected in the solar collectors. Heat collection is determined by solar radiation, collector area, and collector efficiency. Since solar radiation is uncontrollable, collector size and efficiency are the primary design variables. To compare kilns of different sizes, the ratio of solar collector area to lumber volume may be substituted for total collector area. The solar collector area is defined as the area of transparent glazing through which solar radiation passes. The average volume of lumber dried in the six loads was 297 bd-ft, making the average collector to lumber volume ratio 0.088 ft^2/bd-ft. This value is far below the ratios of other kilns reported in the literature which range from 0.209 ft^2/bd-ft (Chudnoff et al. 1966) to 0.744 ft^2/bd-ft (Peck 1962). Plumptre (1967) built three solar kilns with ratios of about 0.167 ft^2/bd-ft, but these included external reflectors and do not fit well into the collector/lumber volume ratio model.

The air-dried boards took an average of 2.5 times longer to reach 30 percent MC and 3.5 times longer to 20 percent MC than the solar kiln-dried boards (Table 5), even though the drying rate in some species was slower in the solar kiln during the initial drying period. Solar drying also enabled the boards to reach a lower final moisture content. Results from other studies indicate similar trends. Plumptre (1967) found approximately equivalent drying rates between solar and air drying to 30 percent MC, but overall air drying took 2.5 to 3 times longer to dry. Peck (1962) and Maldonado and Peck (1962) reported that drying to 20 percent MC was approximately twice as fast for solar drying as air drying. Chen and Rosen (1979) indicated that yellow poplar lumber dried in less time by solar kiln drying than by air drying, but the rate of drying in the kiln was initially quite slow, and air drying to about 45 percent MC was actually faster than solar drying. It was during the later stage of the drying period when solar drying became effective, due to lower relative humidity and higher temperature.

Overall, drying degrade in this study was very low, especially since the lumber was of low quality (No. 2 and No. 3 Common). Average bow, crook, and twist were 0.28, 0.32, and 0.29 percent of length respectively. Cup was 1.29 percent of width. The average number of surface checks per board was 3.1, but most were present in oak. The average number of surface checks per board in species other than oak was 0.6, while in oak the average was 9.9. End checking and end-splitting were very low, averaging less than one per board.

Analysis of variance indicated that species was a highly significant ($P<0.001$) source of variability for green and dried moisture content, warping defects, and surface and end checking. It was not a significant source of end splitting, however, because this was highly significantly related to pith location. Some of the species effect might be attributed to a drying charge class since each charge was dried under different conditions and thickness of the loads varied.

Pith location was the second most important independent variable class. Its effect on green moisture content and dried moisture content is highly significant, due to differences in heartwood/sapwood proportion. The weak, dimensionally unstable juvenile wood generally associated with pith is very subject to cupping, checking, and splitting; therefore, highly significant interrelationships between pith and warping defect are expected. The significant relationship of twist to pith location was probably because the pith in cut lumber rarely ran parallel to the edges. Thus, cupping was uneven along the length, and this led to a certain amount of twisting.

The number of knots in each board was included to serve as an indicator of lumber quality. The relationship between knots and dried moisture content was highly significant, probably because of faster evaporation from exposed grain in boards containing knots. Cupping, twisting, and surface checking may be caused by drying stresses and uneven grain around knots.

Dried moisture content was highly significantly affected by row position of the board, indicating variable air circulation throughout the drying pile. Efforts to minimize this effect by altering stickering spacing, baffling, etc., were unsuccessful because of vent size and fan location. Such problems would not have occurred if the solar kiln had not been retrofitted from an existing structure.

Conclusions

From this study the following conclusions can be drawn:

1. Solar drying can be 2.5 to 3.5 times faster than conventional air drying in Louisiana, depending on the degree of drying required, species, and lumber dimension.
2. Solar drying can be used to dry wood to the 7 to 8 percent moisture content required for indoor use, particularly if thinner boards of non-refractory and easy-to-dry species are used.
3. Solar drying can be used to predry refractory hardwoods at a faster rate than air drying. When the wood is then finished in a conventional kiln, fuel is saved and inventory turnover is faster than in an air drying to conventional kiln drying scheme.
4. Quality of solar dried lumber is good, and drying regrade can be held to acceptable limits.

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